FCF-DOC-002

Science Requirements Envelope Document

Fluids and Combustion Facility Project

March 1999

National Aeronautics and Space Administration
Microgravity Sciences Division
John H. Glenn Research Center
Cleveland, Ohio

Preface

The International Space Station (ISS) Fluids and Combustion Facility (FCF) Project science requirements envelope is defined and controlled herein. This document is the basis for producing and maintaining all FCF specifications.

This document will be maintained under formal configuration control by the FCF Project. Any changes or revisions will be reviewed and approved by NASA Headquarters and NASA MSFC personnel as noted below.

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REVISION AND HISTORY PAGE

REV.	DESCRIPTION	PUB. DATE
-	Final Draft Issued (subsequent to Hardware Concept Review)	June 1998
-	Changes during final document review: Preface Correct wording (change 'are' to 'is') p. ii Insert missing word (par 4; line 5; should read: '... scores of Principal ...') p. 1-5 Correct text (par 2; line 8; remove '-' in 'resources') p. 1-10 Added 2 basis experiments (f15 and f16) to make consistent with scope of engineering verification studies p. 1-11 Reword Req. P15 (line 3; insert missing word; should read: '... Implementation of *suggestions* …') (line 6; misspelled word should read: 'suggestions') p. 1-15 Insert text for new Req. P20 to clarify approach p. 2-2 Delete 2nd paragraph p. 2-6 Modify Req. F1 for clarification (insert 'at least 80%') Rewrite Des. DF1.1 for clarification (insert 'accommodates 100%') p. 2-18 Rewrite Req. F7.1 for detail (insert '…provide at least 500 Watts when required') p. 2-21 Rewrite Req. F9.1 for clarification (insert words 'shall provide laser sources, optical systems, power, and control to enable laser illumination') p. 2-22 Rewrite Req. F11 for clarification (insert words 'provide on-orbit stowage volume having power and cooling to accommodate such needs as thermal control, stirring, and tumbling of experiment samples') p. 2-29 Rewrite Req. F15.1 for clarification (insert words 'provide positioners, optical systems, power, control, and procedures to reproducibly position and align') p. 2-59 Rewrite Req. F27.1 for clarification (insert words 'shall provide non-volatile storage for experiment-specific non-image data as required by Basis Experiments but not less than 9 Gbytes ..') p. 2-61 Rewrite Req. F29 for clarification (add sentence 'At least 16 channels of at least 12 bit analog output shall be provided to experiments that require them.') p. 2-62 Rewrite Req. F31 for clarification (add sentence 'At least 16 channels outputting 1 bit at 5 volts shall be provided to experiments that require them.') p. 4-3 Rewrite Req. O1 for clarification (delete phrase 'sufficient fidelity' and insert 'FCF mission planning and utilization organization shall provide and schedule PI team access to FCF simulators for verification of PI hardware and operations procedures') p. 4-7 Rewrite Req. O16 for clarification (insert '.. on-orbit operations or within 60 days of return from orbit for data that must be physically transferred to Earth') App. A Add two additional Basis Experiments (f15 and f16) App. D Modify/insert text to reflect changes in Chapters 1, 2, 3, and 4 for the above items App. E Reformatted in total; selected data added to make consistent with content of engineering verification studies; 2 basis experiments added (consistent with Table P11 and Appendix A)	June 1998 to March 1999

REV.	DESCRIPTION	PUB. DATE
Base-line	Issued for signature	March 1999

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Introduction

INTRODUCTION

This section describes the purpose, scope, and format of this *Science Requirements Envelope Document* (SRED). It also explains the relationship between this and other key FCF Project documents.

SRED PURPOSE

This *Science Requirements Envelope Document* (SRED) describes the highest level Microgravity Research Program *performance requirements* as well as the Fluid Physics and Combustion Science *scientific requirements* controlling the development, deployment, and operation of the Space Station *Fluids and Combustion Facility* (FCF).

SRED SCOPE

The SRED covers the entire FCF system for its entire life cycle. The FCF system includes flight equipment, ground equipment, software, operational procedures, and all other equipment and activities developed and implemented to meet the requirements. The life cycle extends to ultimate decommissioning and disposal.

The SRED contains requirements that are common to many Fluid Physics and Combustion Science microgravity science experiments. Implementing these requirements will result in a microgravity science facility that can be *customized* to meet the anticipated needs of scores of Principal Investigators (PIs) for scores of experiments.

This document shall be baselined as part of the Requirements Definition Review (RDR) process.

The SRED will be under change control during the FCF development process. The FCF development process ends when all FCF racks have been installed in the Space Station and on-orbit operations of all the racks have begun.

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REQUIREMENTS, CONSTRAINTS, AND DESIRABLE FEATURES

The scientific requirements contained in this SRED are a subset of the full set of requirements and constraints on the design and utilization of FCF. Other sources of requirements and constraints include the following:

- Space Station resource availability
- Space Station requirements (e.g., safety)
- Space Shuttle launch resources
- NASA funding levels
- Technology state-of-the-art
- Microgravity Program Requirements
- ISS Program Requirements
- GRC institutional rules and regulations
- NASA institutional rules and regulations
- Unknowns

The above sources act as constraints on FCF because they are not under the control of the scientific community or FCF Project Management.

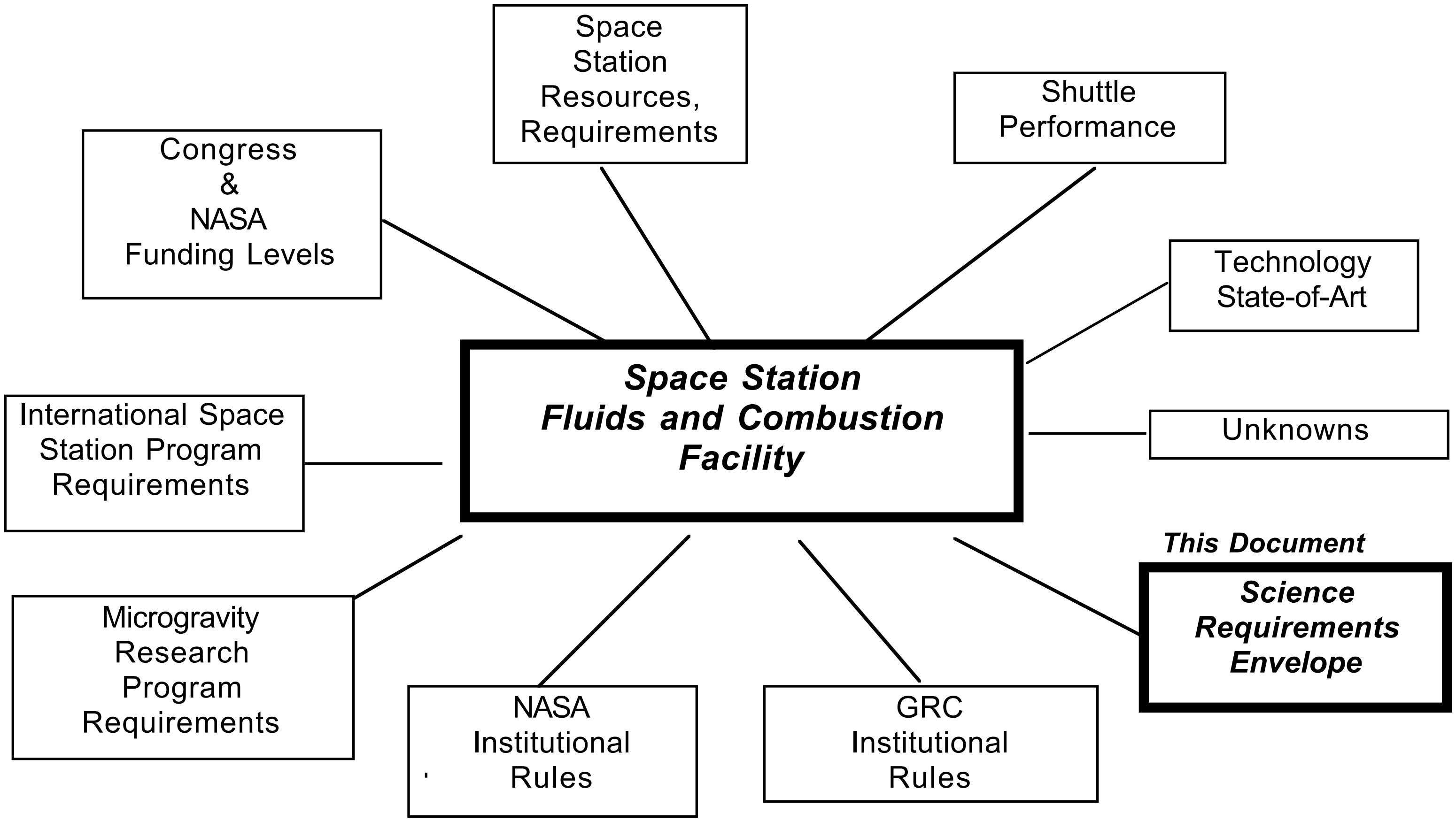
Due to the limitations posed by these constraints, some requirements may prove infeasible. Therefore, in this document, certain FCF features are suggested as desirable (rather than absolutely required). This distinction is made to allow the FCF project some latitude to develop the best possible facility within the constraints. However, it is intended that the FCF team shall attempt to implement all desirable features or, alternatively, attempt to create a facility that will permit their implementation in the future.

Although some desirable features may, ultimately, not be supported, the FCF team shall implement all the features needed to meet requirements specified in this document.

SRED FORMAT

The FCF SRED has, predominantly, a format of alternating pages of narrative and illustration originally developed by the US Air Force for their ‘large project’ descriptive documents. They had found that ‘traditional’ documents did not convey information accurately to the broad spectrum of users, and this was causing cost overruns and non-responsive technical performance. The pictorial format was found to substantially improve communication, and, thereby, lower cost while increasing performance of completed systems.

FCF is using this ‘non traditional’ format for the same reasons as did the Air Force.


Space Station Resources, Requirements
Shuttle Performance
Congress & NASA Funding Levels
Technology State-of-Art
Space Station Fluids and Combustion Facility
International Space Station Program Requirements
Unknowns
This Document
Science Requirements Envelope
Microgravity Research Program Requirements
NASA Institutional Rules
GRC Institutional Rules

SRED AND OTHER FCF DOCUMENTS

This section describes the most notable FCF documents and indicates their purposes. The SRED is the highest level document. The others are developed as a response to it.

- ***Science Requirements Envelope Document***
  The FCF *Science Requirements Envelope Document* (SRED) contains the Microgravity Research Program performance requirements and scientific requirements placed on FCF. FCF must meet these requirements within limits imposed by the technology state-of-the-art, ISS resource constraints, NASA funding constraints, and other relevant constraints. This document also serves a Microgravity Research Program function because all parties and organizations involved with FCF implementation agree to provide their best effort in implementation of the requirements.

- ***Baseline Concept Description***
  The *Baseline Concept Description* (BCD) document provides a description of the International Space Station Fluids and Combustion Facility (FCF) system in an easily understood format of illustration and narrative.

  The FCF system described in the BCD is a response to the requirements stated in the FCF Science Requirements Envelope Document (SRED) and to other requirements and constraints (e.g. ISS resource constraints).

  The BCD is used by all the team members working on the project as a communication tool, and it is used for briefings, studies, and cost estimates.

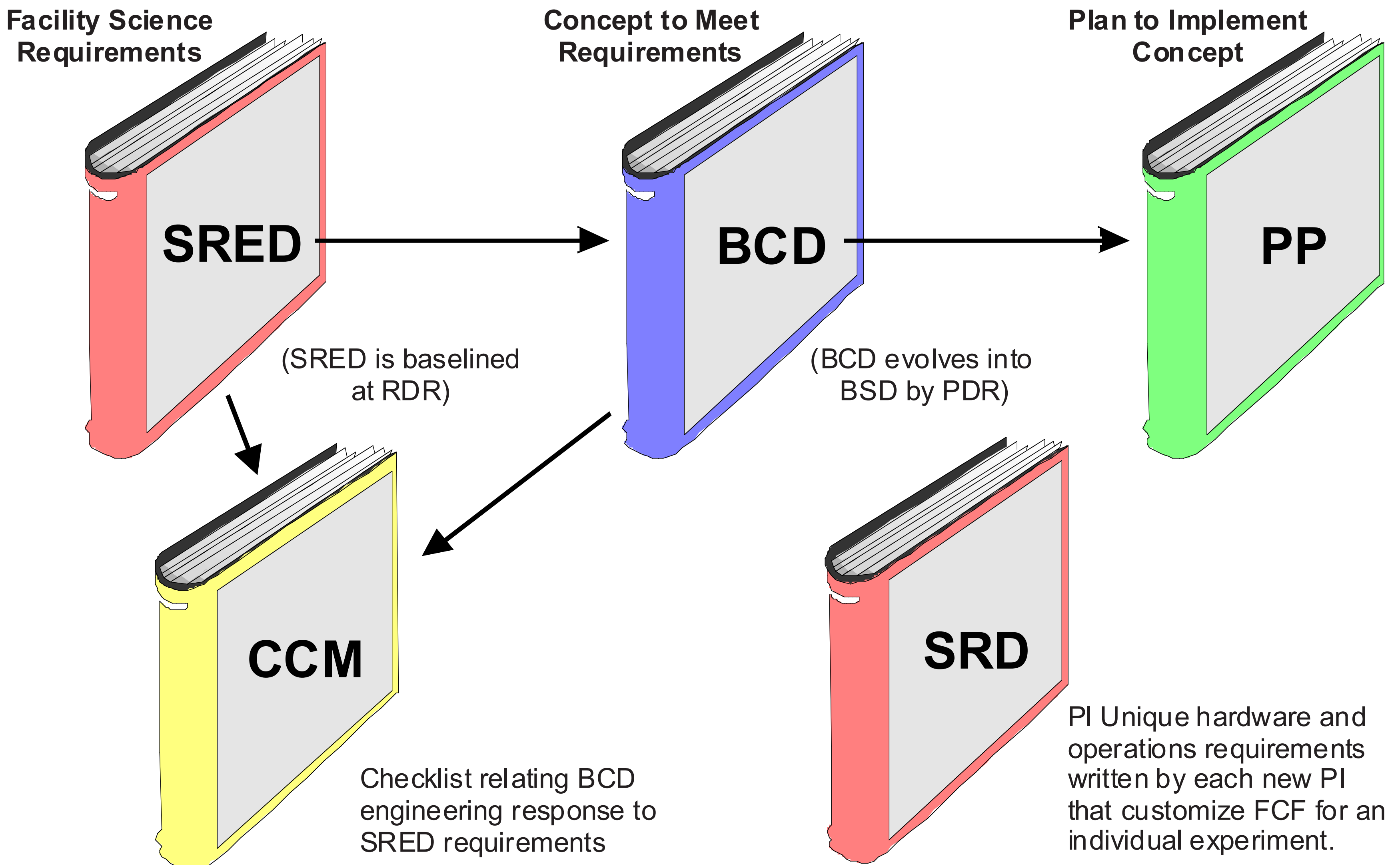
- ***Baseline System Description***
  The BCD evolves into the *Baseline System Description* (BSD) document when the final design concept is presented at the FCF Preliminary Design Review (PDR). At the PDR, the BCD nomenclature is “retired” and the term “BSD” is used to describe the document.

- ***Compliance Matrix***
  The *Compliance Matrix* (CM) is a “check list” document which indicates the correspondence between requirements in the SRED and engineering features described in the BCD (or BSD). It is used to assure that all requirements have been captured by the FCF design.

- ***Project Plan***
  The *FCF Project Plan* (PP) describes the management principles, work breakdown structure, schedule, and budget needed to implement FCF as described in the BCD (or BSD). It is a contract between the FCF Project and the Microgravity Program.

- ***Science Requirements Document***
  Science Requirements Documents (SRD) will be written by the individual Principal Investigators (PI) whose experiments are to be conducted in the FCF. The SRDs define additional, experiment-specific requirements and may describe special hardware needed to customize the facility for each experiment. In some cases, the experiment-specific requirements may exceed those of the SRED - these will be evaluated for inclusion on a case-by-case basis.

Relationship Among FCF Project Documents



Chapter 1 - FCF Level 1 Requirements

1. FCF LEVEL 1 REQUIREMENTS

1.1 INTRODUCTION

This chapter presents the FCF Level 1 requirements as defined by the *Microgravity Research Program Office* (MRPO) and approved by the *Office of Life and Microgravity Sciences and Applications'* Microgravity Research Divison (MRD).

The FCF Level 1 requirements stated herein shall achieve three purposes:

- First, to define required FCF performance at a level of detail that is meaningful to the Program.
- Second, to provide guidance concerning funding and technical constraints within which the performance requirements must be met.
- Third, to provide a set of definitions, rules, and criteria to be applied to the development of lower level FCF science requirements such that the resulting lower level requirements are consistent with Microgravity Program objectives regarding FCF. Note that the concept of the *Basis Experiment* is central to achieving this purpose.

The chapter is organized along the following lines:

- FCF Mission
- FCF Performance Requirements with constraints
- FCF Basis Experiment Definition
- FCF Requirement Envelope Definition Rules

1.2 FCF MISSION AND PERFORMANCE REQUIREMENTS

1.2.1 FCF Mission Requirements

- ***Req. P1***[1]

The Fluids and Combustion Facility (FCF) shall be a permanent on-orbit research facility located inside the United States Laboratory Module (US Lab) of the International Space Station (ISS). FCF shall support NASA Human Exploration and Development of Space (HEDS) Microgravity Research Program objectives. In particular, FCF shall accommodate and facilitate *sustained*, *systematic* Microgravity Fluid Physics and Microgravity Combustion Science experimentation on the ISS for the lifetime of the ISS.

The lifetime of ISS is defined as 10 years with an option to extend to 15 years.

- ***Req. P2***

Fluid Physics and Combustion Science shall be of equal relative priority within the scope of FCF planning, design, operations, and other activities.

It is understood that certain decisions (e.g., rack launch sequence) will necessarily place one of the disciplines in a more favored position, temporarily. Such decisions shall be made so that their cumulative effect does not substantially favor either discipline.

[1] Requirement statements are in bold letters often followed by explanatory text in normal letters.

- ***Req. P3***

FCF shall plan to occupy no more than 3 International Standard Payload Racks (ISPR) located in the US Lab module plus up to 1 additional rack of un-powered stowage, as needed to meet the Level 1 requirements[2].

Prior to FCF Authority to Proceed (ATP), all FCF related mission planning, design concepts, and budgeting shall assume that FCF will have 3 powered racks on-orbit after FCF assembly complete. Moreover, they shall assume a "fair share" of HEDS ISS resources prorated to 3 powered racks. Final allocation of budget and other resources shall occur at appropriate points in the phased review process per NASA and HEDS policy guidelines.

- ***Req. P4***

FCF Level 1 requirements shall take precedence over other scientific and technical requirements.

Should an interpretation of a lower level requirement conflict with a Level 1 requirement, the lower level requirement shall be reinterpreted to be consistent with the Level 1 requirement, or the lower level requirement shall be eliminated at the discretion of the Microgravity Resarch Program Office.

[2] Level 1 Program requirements are designated with a "P" suffix (e.g., P1).

1.2.2 FCF Fluid Physics Performance Requirements

To sustain systematic Microgravity Fluid Physics research on board ISS, the Fluid Physics related aspects of FCF shall accomplish the following level of performance:

- ***Req. P5***

  As ISS and FCF resources become available, FCF shall permit a utilization rate of at least 5 *Basis Experiment* type fluid physics experiments per year while remaining within FCF and ISS resource constraints as understood at the FCF Requirements Definition Review (RDR); however, FCF shall be designed to support a utilization rate of 10 fluid physics experiments per year, should resources permit. FCF compliance to this requirement shall be shown by an analysis indicating that a majority of Fluid Physics *Basis Experiments* could be flown on FCF at a rate of 5 per year within budgetary and ISS resource constraints.

Basis experiments are defined below. Budgetary constraints are defined by the budgetary line items associated with FCF development, operation, upgrade, PI hardware, and PI support. ISS physical resource constraints are defined by the FCF Project's best estimates of critical ISS resource allocations as of FCF RDR (limiting resources shall be identified by the FCF project).

- ***Req. P6***

  As ISS and FCF resources become available, FCF shall accommodate at least 80 percent of the microgravity fluid physics experiments likely to be proposed for FCF. FCF compliance shall be shown by conceptual experiment layouts and analysis indicating that 80 percent of the fluid physics *Basis Experiments* could be accommodated by FCF facility capabilities when augmented by PI hardware capabilities.

In meeting this requirement, it is assumed that some capabilities will be provided by PI hardware that is designed especially for the particular experiment. Unique capabilities, if needed, shall be provided by specialized PI hardware (PI hardware development is not the responsibility of the FCF developer). This requirement is intended to recognize that some science requirements will excessively impact cost or schedule. Nonetheless, every reasonable effort shall be made to accommodate 100 percent of the Basis Experiments.

- ***Req. P7***

  To accommodate potential commercial and international users, FCF shall accommodate at least 5 additional (in addition to Req. P5) fluid physics experiments per year, assuming that PI hardware and other required resources are provided by those users.

Assume that the experiments will be within FCF as-built scientific capabilities. Assume that the budget, upmass, and other resources required for these experiments will be provided by the users from their allocations.

1.2.3 FCF Combustion Science Performance Requirements

To sustain systematic Microgravity Combustion Science research on board ISS, the Combustion Science related aspects of FCF shall accomplish the following level of performance:

- ***Req. P8***

  As ISS and FCF resources become available, FCF shall permit a utilization rate of at least 5 *Basis Experiment* type combustion science experiments per year while remaining within FCF and ISS resource constraints as understood at the FCF Requirements Definition Review (RDR); however, FCF shall be designed to support a utilization rate of 10 combustion science experiments per year, should resources permit. FCF compliance to this requirement shall be shown by an analysis indicating that a majority of combustion science *Basis Experiments* could be flown on FCF at a rate of 5 per year within budgetary and ISS resource constraints.

Basis experiments are defined below. Budgetary constraints are defined by the fiscal year 1996 budgetary line items associated with FCF development, operation, upgrade, PI hardware, and PI support. ISS physical resource constraints are defined by the FCF Project's best estimates of critical ISS resource allocations as of 1996 (limiting resources shall be identified by the FCF project).

- ***Req. P9***

  As ISS and FCF resources become available, FCF shall accommodate at least 80 percent of the microgravity combustion science experiments likely to be proposed for FCF. FCF compliance shall be shown by conceptual experiment layouts and analysis indicating that 80 percent of the combustion science *Basis Experiments* could be accommodated by FCF facility capabilities when augmented by PI hardware capabilities.

In meeting this requirement, it is assumed that some capabilities will be provided by PI hardware that is designed especially for the particular experiment. Unique capabilities, if needed, shall be provided by specialized PI hardware (PI hardware development is not the responsibility of the FCF developer). This 80 percent rule is intended to allow FCF flexibility to exclude requirements that prove infeasible or that excessively impact cost or schedule. None the less, every reasonable effort shall be made to accommodate 100 percent of the Basis Experiments.

- ***Req. P10***

  To accommodate potential commercial and international users, FCF shall accommodate at least 5 additional (in addition to Req. P8) combustion science experiments per year, assuming that PI hardware and other required resources are provided by those users.

Assume that the experiments will be within FCF as-built scientific capabilities. Assume that the budget, upmass, and other resources required for these experiments will be provided by the users from their allocations.

1.3 FCF BASIS EXPERIMENT DEFINITION

The set of FCF *Basis Experiments* is a set of 16 microgravity fluid physics experiments and 11 microgravity combustion science experiments that, taken together, are intended to represent the entire scope of experiments likely to be proposed for FCF during its lifetime on-orbit.

1.3.1 Rationale for Using Basis Experiments

FCF must accommodate a wide range of experiments from two disciplines having a broad variety in types of samples, types of measurements, and other experiment unique factors.

Designing one facility to accommodate this breadth of activities is very challenging (but worthwhile due to economies of scale, which can lower per experiment cost).

One particular challenge is to write an objective set of "facility requirements" which realistically addresses and anticipates all requirements for yet-to-be-defined experiments drawn from such broad disciplines.

There are literally thousands of possible experiments, and the vast majority have not been proposed. Of these thousands, more than one hundred may be accommodated in FCF, depending on its lifetime on ISS. Attempting to deal with such large numbers of potential experiments without having specific requirements is not practical.

To bound this challenging problem, a set of *Basis Experiments* was identified for each discipline and used as a "basis" to encompass the scope of facility capabilities. It must be emphasized that the SRED will not provide detailed science requirements for individual basis experiments. This level of experiment-specific detail will be levied through SRDs written specifically for each flight experiment.

The capabilities defined by the requirements in the SRED are expected to provide an FCF that, when augmented by experiment-specific hardware defined by requirements in the SRDs, accommodates the Fluid Physics and Combustion Science experiments proposed during the lifetime of FCF.

It is intended that the SRED contain requirement envelopes that represent groupings of similar requirements taken from the basis experiments. The information shall be presented in a manner that emphasizes the typical experimental need rather than in a manner that emphasizes the extremes. Thus, an envelope should not be presented as merely the minimum value and the maximum value of a quantifiable requirement. Rather, these groupings shall indicate the values of quantifiable requirements so that a typical need can be ascertained.

In particular, the charts and graphs in the SRED shall be a graphical statement of each requirement. In general, the charts (graphical statements) have more weight than the words in the associated text because they shall define envelopes, or areas of performance. Envelopes of performance are relevant to the design of an adaptable facility because the specific requirements of any future experiment are generally unknown. Consequently, the facility must be adaptable within a range of performance as indicated by the envelope charts.

1.3.2 Fluid Physics Basis Experiments

- ***Req. P11***

  The Fluid Physics Basis Experiments shall be precisely the 16 experiments listed in Table P11.

The Basis Experiments have been carefully selected, and FCF shall be designed to accommodate them when FCF on-orbit assembly is complete. Subsequent to baselining of this SRED, no changes shall be made to this list without a formal change process involving approval of all the signatories to the FCF SRED.

Fluid physics is composed of a number of different areas of study. Areas that can potentially benefit from microgravity research include, but are not limited to:

- interfacial phenomena
- thermocapillarity
- colloids
- complex fluids
- electrohydrodynamics
- multiphase flow
- granular media
- critical fluids (second order phase transformations)
- phase change (first order phase transformations)
- diffuso-capillary phenomena

In response to NASA Research Announcements (NRA), NASA has received proposals from the science community for microgravity research in each of the above areas.

To assure that a representative sample of experiments is considered in defining FCF requirements, the set of fluid physics *Basis Experiments* was chosen to span the areas listed above. The requirements envelope for the Fluids Facility portion of FCF shall be based on the basis experiments which were selected as follows.

- Peer-reviewed Science Requirements Documents (SRDs) from existing investigations.
- Descriptions of peer-reviewed microgravity fluid physics flight investigations in the flight definition phase as of March, 1999.
- Experiment descriptions from scientists conducting Research and Analysis microgravity fluid physics investigations as of March 1999.
- Feedback from the Microgravity Fluid Physics Discipline Working Group.

Following figure lists the fluids basis experiments. The experiment numbers correlate with the numbering system in Appendix A (example: Sect. A2.14 is experiment f14).

TABLE P11 - FLUID PHYSICS BASIS EXPERIMENTS

Section#	Exp.#	Experiment Name	Relevant Area
A2.1	f1	Thin Film Fluid Flows at Menisci	• Interfacial Phenomena/Phase Change
A2.2	f2	Contact Line Hydrodynamics	• Interfacial Phenomena
A2.3	f3	Rheology of Non-Newtonian Fluids	• Complex Fluids
A2.4	f4	Dynamics of Hard Sphere Colloids	• Colloids
A2.5	f5	Colloid Physics	• Colloids
A2.6	f6	Studies in Electrohydrodynamics	• Electrohydrodynamics
A2.7	f7	Nucleation and Growth of Microporous Crystals	• Phase Change/Morphology
A2.8	f8	Interactions of Bubbles and Drops	• Thermocapillarity
A2.9	f9	Thermocapillary Motion of Bubbles and Drops	• Thermocapillarity
A2.10	f10	Interfacial Transport and Micellar Solubilization	• Diffuso-capillary
A2.11	f11	Thermocapillary and Double-Diffusive Phenomena	• Thermo-Diffuso-Capillary
A2.12	f12	Critical Point Phenomena	• Complex Fluids/Phase Change
A2.13	f13	Multiphase Flow Boiling	• Multiphase Flow/Phase Change
A2.14	f14	Mechanics of Granular Media	• Granular Media/Complex Fluids
A2.15	f15	Shear Rheology of Complex Fluids	• Complex Fluids
A2.16	f16	Mesoscopic Studies of Colloids and Complex Fluids	• Colloids

1.3.3 Combustion Science Basis Experiments

- ***Req. P12***

  The Combustion Science Basis Experiments shall be precisely the 11 experiments listed in Table P12.

The Basis Experiments have been carefully selected, and FCF shall be designed to accommodate them when FCF on-orbit assembly is complete. Subsequent to baselining of this SRED, no changes shall be made to this list without a formal change process involving approval of all the signatories to the FCF SRED.

Combustion science is composed of a number of different areas of study. Areas that can potentially benefit from microgravity research include, but are not limited to:

- laminar flames
- reaction kinetics
- droplet and spray combustion
- flame spread
- fire and fire suppressants
- condensed phase organic fuel combustion (including coal combustion)
- turbulent combustion
- soot and polycyclic aromatic hydrocarbons (PAH)
- materials synthesis
- detonations and explosions

In response to NASA Research Announcements (NRA), NASA has received proposals from the science community for microgravity research in each of the above areas.

To assure that a representative sample of experiments is considered in defining FCF requirements, a set of combustion *Basis Experiments* was chosen to span the areas listed above. The requirements envelope for the Combustion Facility portion of FCF shall be based on the basis experiments which were selected as follows.

- Peer-reviewed Science Requirements Documents (SRDs) from existing investigations.
- Descriptions of peer-reviewed microgravity combustion science flight investigations in the definition phase as of March, 1999.
- Experiment descriptions from scientists conducting microgravity combustion science investigations as of March, 1999.
- Feedback from the Microgravity Combustion Science Discipline Working Group.

Following figure lists the combustion basis experiments. The experiment numbers correlate with the numbering system in Appendix B (example: Sect. B2.10 is experiment c10).

TABLE P12 - COMBUSTION SCIENCE BASIS EXPERIMENTS

Section#	Exp.#	Experiment Name	Relevant Area
B2.1	c1	Gas-Jet Diffusion Flames	• laminar flames • turbulent combustion
B2.2	c2	Structure of Flame Balls at Low Lewis Numbers	• laminar flames • reaction kinetics
B2.3	c3	Spread Across Liquids	• condensed phase organic fuel combustion • flame spread and fire suppressants
B2.4	c4	Diffusive and Radiative Transport in Fires	• condensed phase organic fuel combustion • flame spread and fire suppressants • laminar flames
B2.5	c5	Smoldering Combustion	• condensed phase organic fuel combustion • flame spread and fire suppressants
B2.6	c6	Droplet Combustion	• droplet and spray combustion • reaction kinetics
B2.7	c7	Laminar Soot Processes	• laminar flames • soot and polycyclic aromatic hydrocarbons
B2.8	c8	Soot Measurement in Droplet Combustion	• droplet and spray combustion • soot and polycyclic aromatic hydrocarbons
B2.9	c9	Unsteady Burning of Contained Reactants	• laminar flames • reaction kinetics
B2.10	c10	Solid Fuels Flammability Boundary	• laminar flames • reaction kinetics • condensed phase organic fuel combustion • flame spread and fire suppressants
B2.11	c11	Radiative Ignition and Transition to Flame Spread	• laminar flames • reaction kinetics • condensed phase organic fuel combustion • flame spread and fire suppressants

1.3.4 FCF Requirement Envelope Definition Rules

This section defines the rules that shall be used to classify the scientific requirements, desired capabilities, and suggested technical approaches derived from an evaluation of the Basis Experiments.

The FCF SRED should contain, as requirements, only those items having scope and content consistent with the broad definition of a microgravity science facility that will support many individual experiments. Furthermore, some of the basis experiments themselves have not been fully developed. Consequently, the quantification of their individual requirements is approximate. Therefore:

- ***Req. P13***

  The FCF Science Requirements Envelope Document (SRED) shall present Basis Experiment requirements collectively.

In other words, similar requirements (obtained from individual Basis Experiments) shall be grouped by type (e.g., image resolution). These groupings shall be presented and discussed in the SRED collectively without emphasizing individual requirements from individual Basis Experiments.

- ***Req. P14***

  The FCF developer shall consider the requirements of a given type collectively in formulating concepts and approaches to compliance. Extreme requirements for single experiments should not bias the compliance in a manner that adversely affects integrity or cost effectiveness of the design.

An extreme case is a requirement that serves less than two Basis Experiments and lies at the edge of the envelope. The intent of this requirement is in keeping with P6 and P9.

- ***Req. P15***

  The FCF project's highest priority shall be to meet requirements followed by implementing desired capabilities. Implementation of suggestions included in the accompanying text need not have priority in shaping the compliance response; however, such suggestions should be seriously considered while making trade-off decisions for alternative approaches to compliance.

To facilitate an orderly approach to indexing and tracking the FCF requirements, desired capabilities, and goals, the following numbering scheme shall be used:

Programmatic Requirements	P1..Px
Fluid Physics Requirements	F1..Fx
Combustion Science Requirements	C1..Cx
Operations Requirements	O1..Ox

Desired capabilities are identified by prefixing the above with a "D". For example,

Fluid Physics Desired Capability	DF1

1.3.4.1 Criteria for Definition of Requirements

In defining the requirements for the FCF, some requirements will be broadly applicable to many Basis Experiments, while others will only apply to one or two or a small subset of Basis Experiments.

- ***Req. P16***

  To be an FCF science requirement an item shall meet the following minimum criteria:

  1. **The requirement shall be stated as (or be interpretable as) a functional capability**. Examples: a requirement could be stated as an ability to measure a given parameter with a given accuracy, or a requirement could be stated as a capability to provide laser lighting at certain wavelengths and power levels
  2. **At least one Basis Experiment will fail if the requirement is not met.** It sometimes appears tempting to 'push the state of the art' in projecting capabilities into the future, this definition criterion implies that a valid requirement must be driven by at least one clear application of the required capability. The burden of proof regarding this criterion is on the person or group proposing the requirement.
  3. **Inspection, analysis, or test can objectively verify how well FCF meets the requirement.** Acceptable verification methods for each requirement are *suggested* in Appendix D of this document. The FCF developer may propose to use different verification methods (subject to approval by FCF project management and discipline scientists).

1.3.4.2 Criteria for Definition of Desirable Capabilities

It is anticipated that some very desirable capabilities will not meet the rigorous criteria defining a requirement; therefore, they cannot be called requirements. However, these desirable capabilities should be considered when designing FCF.

- ***Req. P17***

  To be a valid FCF desired capability or feature an item shall meet the following minimum criteria:

  1. **Does not qualify as a requirement.**
  2. **Supported by objective data indicating that at least two Basis Experiments would have substantially greater scientific yield if the desired capability were implemented.** It sometimes appears tempting to 'push the state of the art' in projecting capabilities into the future, this definition criterion implies that a valid desired capability must be driven by benefits to more than one clear application. The burden of proof regarding this criterion is on the person or group proposing the capability or feature.
  3. **Inspection, analysis, or test can objectively verify how well FCF provides the capability.** Acceptable verification methods for each desired capability are *suggested* in Appendix D of this document. The FCF developer may propose to use different verification methods (subject to approval by FCF project management and discipline scientists).

1.3.4.3 Suggested Engineering Implementations

Science Requirements may contain a reference to particular technologies or specific engineering solutions that might be used to implement them. This section provides guidance regarding technology references and engineering solutions associated with Science Requirements.

Effective communication often requires the use of concrete examples. Without examples, a brief statement of a requirement could be interpreted differently by different readers. In some cases, giving an implementation example may best state a scientific functional requirement. Such s*uggested* engineering implementations of the requirement enable the engineers to better understand the intent of the underlying functional requirement.

FCF is not required to incorporate suggested engineering implementations as-stated because technology is constantly improving, and a technology suggested today may not be the best one to use when FCF is built. Moreover, different engineering solutions suggested for meeting different requirements may be mutually exclusive. However, FCF shall endeavor to ascertain the underlying functional requirement implied by the suggested implementation and meet that functional requirement.

- ***Req. P18***

  Specific technologies or engineering solution verbiage associated with the FCF science envelope requirements do not constitute requirements on the FCF project team to implement that technology or solution.

For example, a proposed requirement to provide a HeNe laser with a given power output should be considered as a suggested engineering implementation which *implies* a valid functional requirement. The valid functional requirement extracted from the basis experiments may be: To provide light at a specific wavelength, at a given intensity, beam uniformity, and coherence. The FCF developer may meet the implied functional requirement by using the suggested implementation or by a different implementation, at the FCF developer's discretion.

- ***Req. P19***

  The FCF developer shall endeavor to ascertain the underlying functional requirement implied by a suggested implementation and meet that functional requirement – provided that the implied requirement meets Req. P16. The developer shall use similar logic for implied desired capabilities which shall meet Req. P17.

When documenting compliance with the scientific requirements in this SRED, the FCF developer should state the original requirement and, if necessary, also state the developer's interpretation of the implied requirement or desired capability. This interpretation will be subject to review and approval by the appropriate FCF Discipline Scientist with concurrence by the FCF Project Manager. After approval, it will be satisfactory if the developer shows compliance to the developers interpretation.

- ***Req. P20***

  Compliance to science requirements must be shown by the completed facility. Generally, the approach to indicating compliance centers on analysis of FCF's ability, augmented by PI hardware, to perform the Basis Experiments while providing the capabilities implied by the science requirements. Subsequently, the completed hardware shall be tested to verify the hardware performance assumed for the analyses.

For many requirements, compliance can be inferred from analysis of the FCF detail design and a few tests. For example, the ability to read a given number of A/D channels to a given precision can be confirmed by indicating the presence of the required A/D hardware combined with an as-installed (in the flight unit) test of the A/D hardware & software which indicates the needed accuracy, precision, absence of noise, and etceteras. On orbit, how the channels will be used and perform depends on a particular experiment implementation and PI hardware which is unknown; therefore, a more specific evaluation is not justifiable.

For some requirements, compliance involves proving that FCF can be set up, including the PI hardware and operations concept, to perform a generic class of experiment while meeting the requirement. Often, geometry and available volume limit what can be accomplished. In these cases compliance shall be indicated by conceptually laying out an appropriate subset of the Basis Experiments (described in Appendices A and B) in the FCF racks (on paper or in a computer model) and demonstrating (by analysis) that the experiments' requirements could theoretically be met using the conceptual layout. Of course, the relevant FCF flight components must be tested to prove that they individually perform to the standard assumed for the analysis. The experiment layout concepts and analyses shall be best efforts. Concepts shall be developed for all the Basis Experiments. These concepts can be reused to show compliance to each requirement and requirement envelope.

Chapter 2 - Fluids Physics Requirements Envelope

2. FLUIDS REQUIREMENTS ENVELOPE

2.1 INTRODUCTION

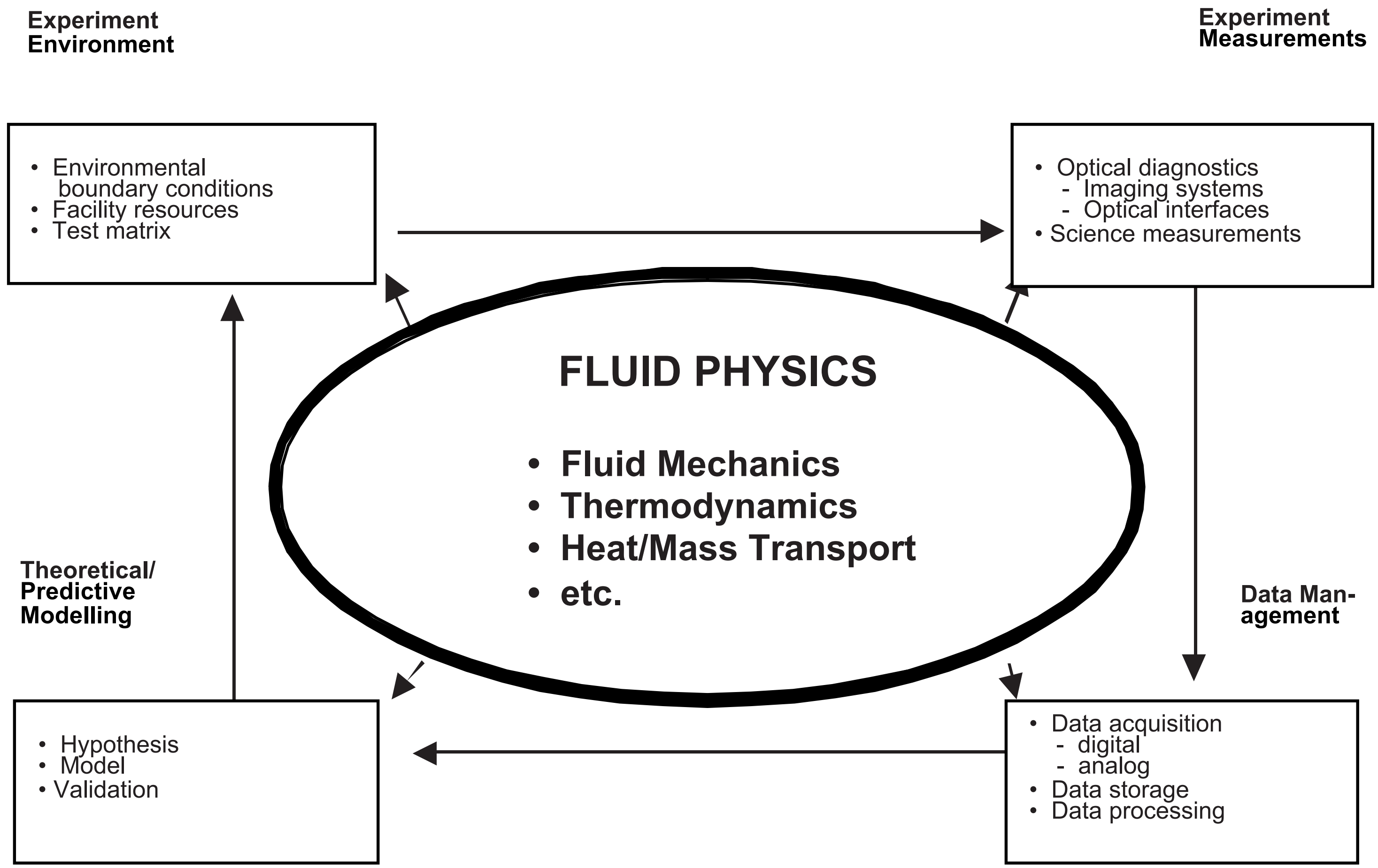
The purpose of this chapter is to present a description of the requirements placed on the Fluid Physics portion of the Fluids and Combustion Facility (FCF). This is a top-level description that is intended to "envelope" requirements for necessary capabilities of use to most (if not all) experiments. The "envelopes" are comprised of selected detailed requirements from the Basis Experiments described in Appendixes A and E.

This section is divided into the following subsections:

- **Experiment Environment (Section 2.2)**: These are requirements on parameters that define the conditions in which the experiment is conducted.
- **Experiment Measurements (Section 2.3)**: These are requirements on parameters to be measured during the course of the experiment.
- **Data Management (Section 2.4)**: These are requirements on the acquisition and management of data acquired in the course of the experiment.

Facing figure shows a graphical representation of the experimental process which has been used to organize the requirements which follow. The SRED addresses Experiment Environment, Experiment Measurements, and Data Management. Theoretical and predictive aspects are not part of the facility SRED; they would be addressed in SRDs for individual experiments.

Experiment Process Model



2.2 EXPERIMENT ENVIRONMENT

The requirements discussed in this section pertain to facility generic support systems and to conditions under which experiments are to be conducted. This includes most of the physical bounds necessarily imposed by the facility, the operating environment, the scope of support services, and adequate operations time to accommodate each experiment.

The following parameters are presented below in terms of requirement envelopes that are generated in terms of the basis experiments included in this document.

- **Physical Environment (2.2.1):** The facility must provide generic capabilities to accommodate the mechanical installation of each experiment and the thermal and acceleration environment.
- **Facility Resources (2.2.2):** The facility must provide a basic set of resources including power, cooling, vacuum, communications, etc. to support experiment operations.
- **Test Time and Duration (2.2.3):** The facility must provide adequate volume, power and environmental control to accommodate experiment operations.

The following is a list of the requirements in this section that relate to the Experiment Environment:

Section 2.2.1 - Physical Environment:

Req. F1 Work volume For Science

Req. F2 Experiment Test Cells

Req. F3 Acceleration/Vibration Environment

Req. F4 Environmental Temperature

Req. F5 Air Flow

Req. F6 Cleanliness

Section 2.2.2 - Resources:

Req. F7 Power

Req. F8 Background Lighting

Req. F9 Laser Light Illumination

Req. F10 Vacuum

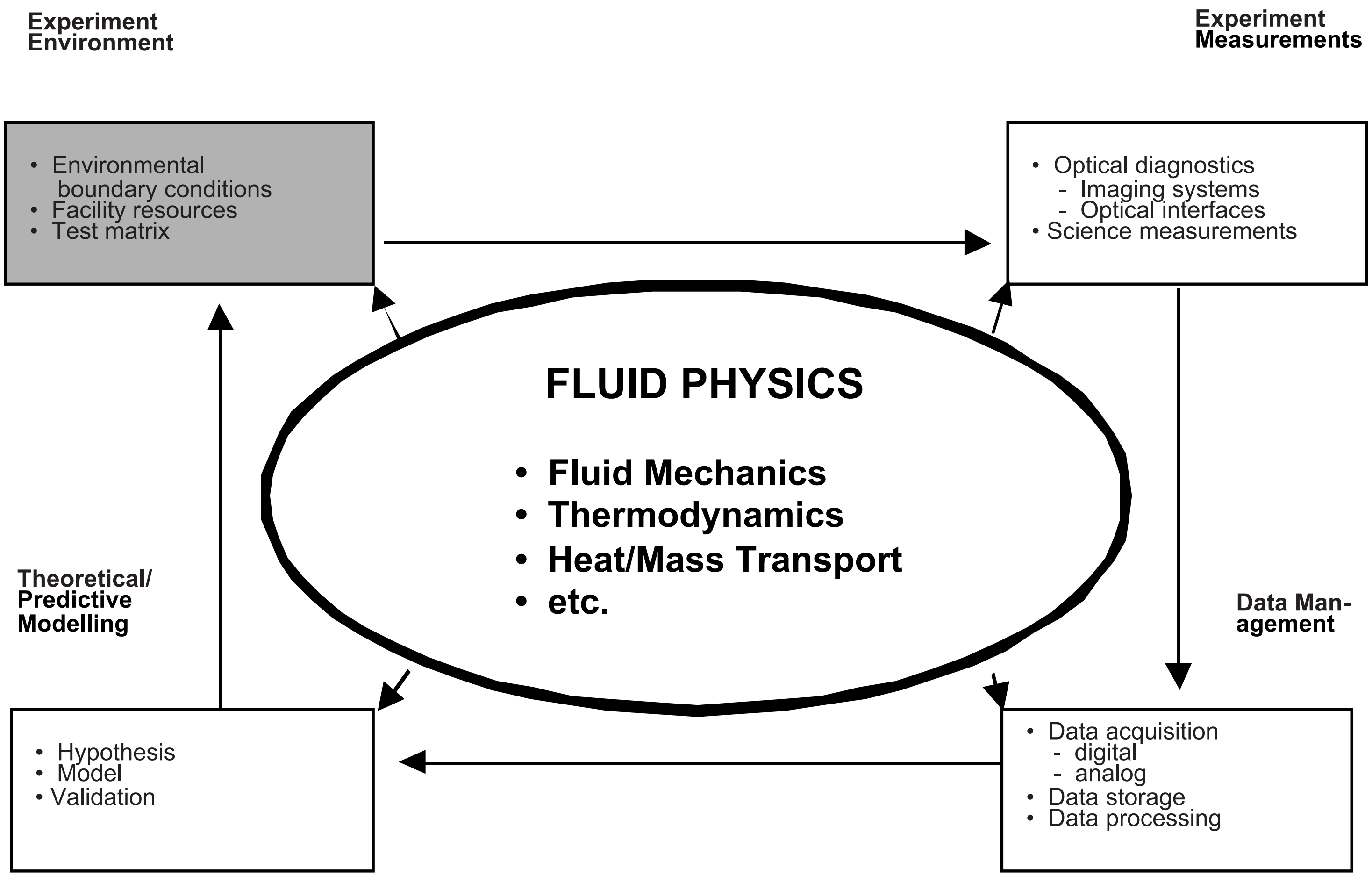
Req. F11 Stowage

Section 2.2.3 - Test Time and Duration:

Req. F12 Number of Tests/Test Durations

Facing figure illustrates the experimental process previously shown with the Experiment Environment (this Section 2.2) highlighted. All requirements related to this environment are in this section.

Experiment Process Model



2.2 - EXPERIMENT ENVIRONMENT (cont.)

2.2.1 Physical Environment

- ***Req. F1 - Work volume for Science***

  FCF shall provide a work volume dedicated to Fluid Physics experimentation. A majority of this volume shall nominally be set aside for PI hardware that may be unique to a specific experiment. The volume set aside shall be adequate to allow set-up and operation of at least 80% of the Fluid Physics Basis Experiments.

Examples of PI hardware include (but are not limited to) fluid sample cells, custom power supplies, amplifiers, chillers, dedicated computers, and diagnostics. Some estimates of PI sample cell sizes are contained in Appendix E. Often, many of these items may be integrated into a single larger container by the PI team, and room shall be provided for such a container in the FCF-supplied work volume.

- ***Des. DF1.1***

  It is desired that FCF provide a Fluid Physics work volume that will accommodate 100% of the Fluid Physics Basis Experiments.

This work volume, in the FCF rack where Fluid Physics experiments are performed, should be as large as possible. If feasible, use should be made of ISS stowage and other FCF racks to increase the available work volume in the FCF rack where Fluid Physics experiments are performed.

The work volume is defined as the open volume remaining for mounting PI hardware after accounting for all structure and FCF subsystems. The work volume should be contiguous and be roughly the shape of a rectangular solid.

- ***Des. DF1.2***

  It is desired that the facility be able to concurrently accommodate at least 2 experiments within the work volume, each having its own diagnostic system.

It is suggested that there should be the ability to control, in parallel, the operations of at least two experiments in the work volume. Operations in this sense means all command, control, telemetry, and data logging with no compromise for either experiment.

- ***Des. DF1.3***

  It is desired that FCF provide multiple options for mounting PI hardware within the work volume and provide procedures that allow the positions of critical PI hardware elements to be established.

Examples of position critical hardware include the experiment sample, lenses, and light sources. It is suggested that knowing the absolute positions to within plus or minus 2mm would be adequate.

- ***Des. DF1.4***

  It is desired that FCF provide at least one level of containment for laser light (or other bright lights) that might pose a crew health hazard during experiment operation. Additional levels of containment, if required, may be provided by PI hardware.

- ***Des. DF1.5***

  It is desired that FCF provide a temporary level of containment for fluids originating in PI hardware during experiment set up, reconfiguration, and test cell change-out.

It is suggested that this temporary containment will provide a glove-box-like function to allow manipulation of PI samples. The facility should provide containment at the level of the largest practical volume (by providing large research module units that address containment, optical and other interfaces, and transportation and integration concerns).

- ***Des. DF1.6***

  It is desired that FCF be capable of providing at least one level of containment for particulates larger than 1.0 mm originating from PI hardware during experiment operation.

- ***Des. DF1.7***

  It is desired that FCF provide capabilities for gas sampling of and atmosphere circulation within the work volume that are similar to and compatible with analysis and filtration systems in the Combustion Element of FCF.

The intent is to be able to use FCF combustion hardware for gas analysis and clean up, if needed.

2.2.1 Physical Environment (cont.)

- ***Req. F2 - Experiment Test Cells***

  FCF shall be capable of accommodating fluid physics PI hardware test cells and containers in the range of sizes and capabilities required by the basis experiments.

Experiment-specific hardware that directly contains the fluid samples is, herein, designated as a "test cell". Note that the total volume of the PI-specific hardware (including the test cell) may be larger when experiment-specific sub-system volumes are also considered. As mentioned previously, some indication of experiment test cell sizes are given in Appendix E.

The following suggestions are made regarding the test cell and container sizes that would accommodate the fluid physics basis experiments'.

- The facility should accommodate test cell sizes of at least 40 x 40 x 30 cm (w x h x d)), and consider adaptability of such test cells within mid-deck lockers, Express racks, and other potential transport rack locations. These dimensions should be consistent with the research module that would provide one level of containment. Test cells in excess of the above mentioned baseline size could be accommodated with reductions in facility-provided imaging capabilities.
- The facility should accommodate PI-specific hardware packages up to approximately 75 x 100 x 40 cm (w x h x d)) when facility-provided imaging and illumination services are not required.

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2.2.1 Physical Environment (cont.)

- ***Req. F3 - Acceleration and Vibration Environment***
- ***Req. F3.1***

  FCF shall be capable of providing a microgravity environment (at the test sample) that accommodates the envelope of limiting accelerations identified for the fluid physics basis experiments. Operational protocols may be used to support compliance with this requirement (e.g., scheduling to avoid major disturbances). Figures F3a and F3b are graphical statements of the requirements to be enveloped. Figure F3a illustrates the approximate upper limits on quasi-steady acceleration for each basis experiment. Figure F3b illustrates the excluded zone for g-jitter.

Detailed microgravity experiment requirements are not clearly defined for all basis experiments. Based on analysis, presumed limits for quasi-steady state accelerations are defined for most experiments and those limits fall within the range 10^{-6} to 10^{-2} g/g_0. Constraints on vibratory and impulse excitations are not defined explicitly for the basis experiments but are believed to be consistent with the NASA Code UG specification (SSP 41000).

- ***Req. F3.2***

  FCF shall accommodate an acceleration measurement device as close as practical to the test cell. It shall be capable of measurements in three simultaneous orthogonal directions at levels from 10^{-2} to 10^{-6} g/g_0 and frequencies from 0.01 to 300 Hz. Accuracy shall be within 10 percent of selected full scale acceleration range. The data shall be available in near real time and post mission.

It is suggested that the Space Acceleration Measurement System II (SAMS II) accelerometer be considered for vibratory and impulse acceleration measurements**.**

Facing figure displays the maximum quasi-steady accelerations acceptable to the basis experiments.

Maximum Quasi-steady g-Level Limits

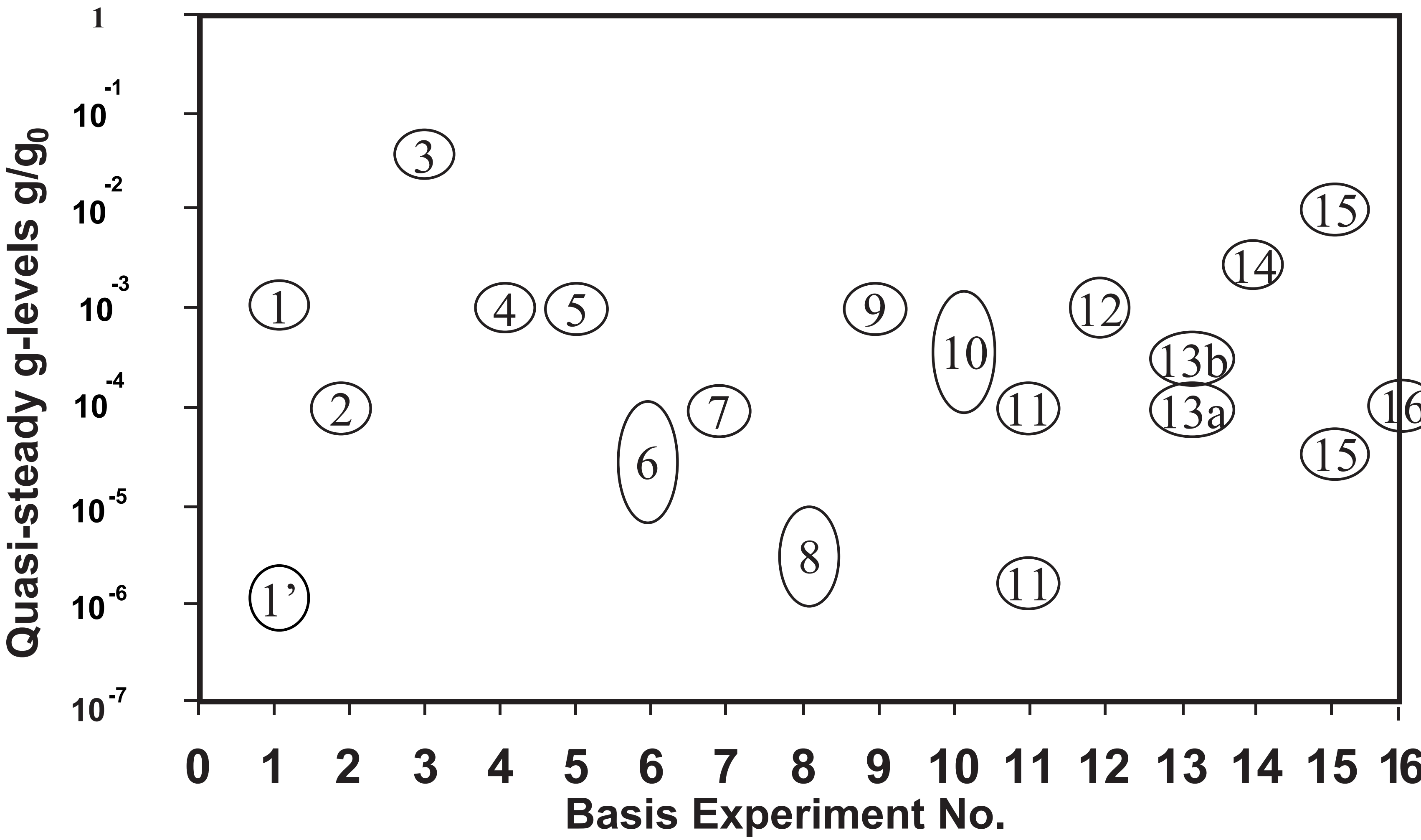

Figure 3a

- ***Req. F3 - Acceleration and Vibration Environment*** *(cont.)*

Facing figure depicts disallowed resonant vibrations for the basis experiments.

g-Jitter Exclusion Envelope for Fluids Experiments

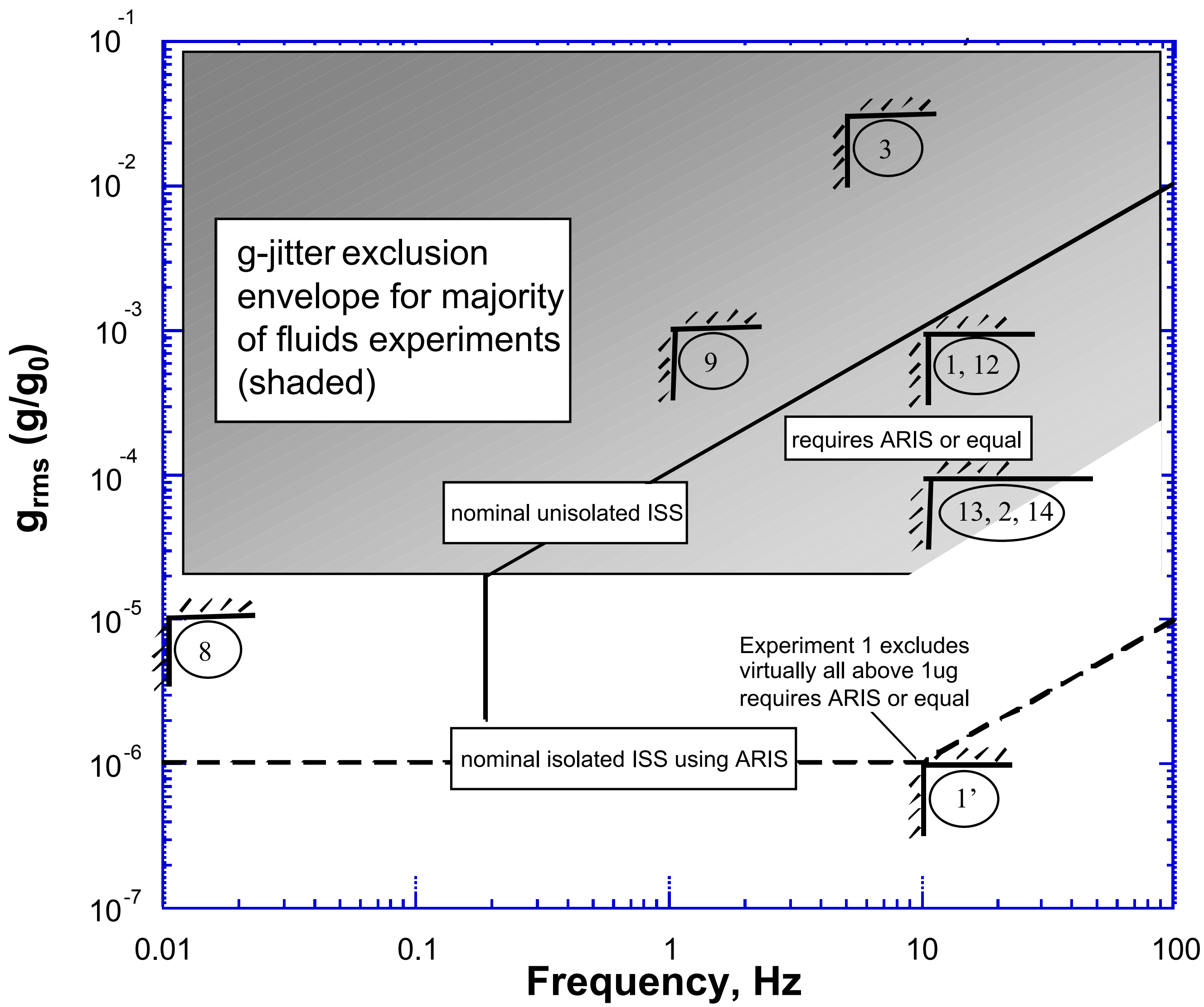

Figure 3b

2.2.1 Physical Environment (cont.)

- ***Req. F4 - Environmental Temperature***
- ***Req. F4.1***

  FCF shall provide stable temperatures within the fluid physics work volume in the range of 20 to 30 C during periods of operation.

To provide an appropriately stable operating environment for precision measurements (particularly for optical systems whose settings will drift with temperature changes), it is necessary that the work volume temperatures be stable (time invariant) at, essentially, "room temperature". This temperature stability requirement does not imply that the precise temperature be settable as with a thermostat. It is expected that FCF will perform an analysis demonstrating that the temperature stability needs of the basis experiments will be met.

It is suggested that the work volume temperature stability of plus or minus 1 C degree should be routinely achievable. It is likely that meeting this requirement may require an active heating and/or cooling system inside the rack.

More precise temperature control will be maintained at the test cell by the PI hardware.

- ***Req. F4.2***

  The facility shall support the ability of PI hardware to maintain required test cell (and other) temperatures inside the PI hardware over a minimum range of -20 to 100 C.

It is expected that, while operating in this controlled environment, PI sample temperatures will be independently controlled to experiment-specific precision over a large range (-20 to +100°C for the basis experiments) by the PI-provided hardware. Thus, to meet the requirement, FCF should provide controllable power, controllable cooling, analog measurement capability and a means of interfacing those resources to PI hardware temperature measurement and control subsystems.

- ***Des. DF4.1***

  It is desired that the facility measure the relative humidity, accurate to within +/- 10%, in the work volume.

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2.2.1 Physical Environment (cont.)

- ***Req. F5 - Air Flow***

  FCF shall provide the capability to control air circulation within and around measurement systems that are susceptible to disturbance caused by uncontrolled air circulation. At times the air must be still and at times it must be circulated to obtain relatively uniform conditions.

Precise optical and thermal measurements can be affected by density gradients in the transmitting medium and by fluctuations in thermal and density fields due to moving air during periods of measurement. For the most precise measurement requirements, it will be necessary to control the movement of air in the vicinity of the sample and optical systems.

Under the still-air condition, there would be reduced thermal fluctuations for optically sensitive experiments, and enhanced optical cleanliness.

Under the forced-flow condition, thermal management in the work volume would become easier, facilitating simpler PI specific hardware design, and easier use of COTS hardware.

- ***Req. F6 - Cleanliness***

  FCF shall provide physical and procedural controls to limit levels of contamination on the optical elements of optical systems during handling, setup, operation, and storage. Optical element transmission shall remain greater than 60 percent of the day 1 value (previously verified). Replacement of contaminated elements can be used as one aspect of control.

The primary measurement tools for many experiments involve optical systems and components that can be degraded by surface contamination. There are many sources of contamination (e.g., handling, air-borne particles, condensable vapors, and creep of local lubricants and solvents). The more desirable concepts for implementing PI specific optical diagnostic systems involve manipulation of unprotected optical elements and, therefore, every experiment will be susceptible to the effects of such contamination.

Of particular concern are "facility optics" which may remain on-orbit for extended times and be used as part of many experiments. The degradation in performance due to cumulative contamination could prohibit acceptable levels of transmission and scattering.

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2.2.2 Resources

- ***Req. F7 - Power***
- ***Req. F7.1***

  FCF shall provide PI-provided hardware with adequate power per the estimates shown in figure F7. At a minimum, this power shall be 500 W for a period of weeks (when needed) and 1000 W for periods of at least 15 minutes (when needed). Figure F7 is a graphical statement of the requirements.

The broad scope of fluids experiments includes a wide range of instrumentation and controls and, therein, a wide range of power demands. The accompanying figure gives estimates of the power required for the basis experiments.

- ***Req. F7.2***

  FCF shall provide 5 (or more) individually controlled sources of electric power for use by PI hardware (minimum capability would be five 28 volt, 4 amp circuits).

- ***Req. F7.3***

  FCF shall provide PI hardware with easy access to cooling adequate to dissipate the power provided to the PI hardware. Access to both liquid cooling and air cooling is required.

Depending on the specific experiment, PI hardware may require liquid cooling to maintain a "still air" environment (e.g., when certain optics are employed). At other times, circulating cooled air may be the best solution.

- ***Des. DF7.1***

  It is desired that FCF provide the ability to implement a "sleep" mode on PI-provided circuit cards (particularly those PI-provided cards used in facility computers) to selectively conserve power resources during low levels of use.

This desire may affect the choice of facility computer hardware.

The facing figure indicates the range of power estimated to be required by the basis experiments.

Power Requirements For the Basis Experiments

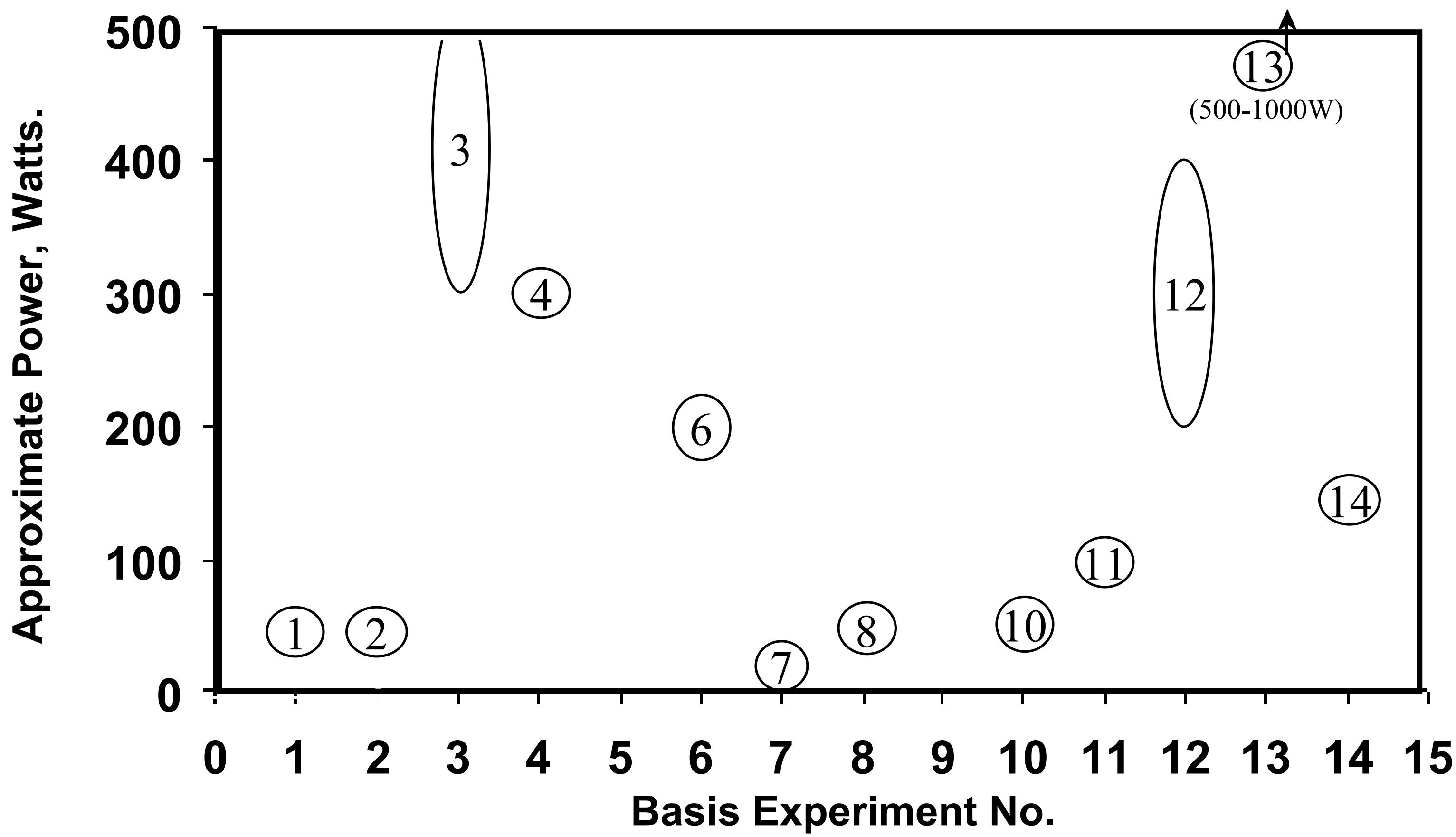


Figure F7

2.2.2 Resources (cont.)

- ***Req. F8 - Background Lighting***

  FCF shall provide uniform, broad band lighting (nominally white light) at the test cell. Intensity and uniformity shall be consistent with image resolution requirements. The absolute mean intensity shall be variable over a wide range. The mean intensity shall be determinable with an accuracy of approximately 1 percent before, during, and after an experiment test point run. The mean intensity shall be stable within approximately 1 percent during a test point run.

  The dimensions of the illuminated area shall be capable of adjustment over a range of sizes as required by the basis experiments; however, the nominal size shall be an approximately 10cm x 10cm illuminated field of view.

Most of the Fluid Physics experiments will use images as the primary science data. Images are nothing more than manifestations of variations in light intensity on the recording media. Consequently, the absolute intensity, intensity uniformity, and intensity stability of the FCF light sources is of paramount importance.

It is suggested that the range of adjustment of the background lighting field of view be from under 1cm diameter up to 30cm diameter, perhaps with PI hardware.

It is expected that the intensities required would range from 0.01 to 10 mW/cm^2 (typically 1 mW/cm^2). Adjustments can be either continuous, step-wise, or a combination, whichever proves most practical.

Intensity stability implies time invariance.

- ***Des. DF8.1***

  It is highly desirable that the standard deviation from mean intensity of the uniform background lighting be less than 0.2 percent (9 bit).

- ***Des. DF8.2***

  It is desired that the illumination not limit the optical resolution and not cause ringing in the image (i.e., the light should be, at most, partially coherent).

2.2.2 Resources (cont.)

- ***Req. F9 - Laser Light Illumination***
- ***Req. F9.1***

  FCF shall provide laser sources, optical systems, power, and control to enable laser illumination over the range of wavelength, polarization, power, and other characteristics required by the majority of fluid physics basis experiments. The facility shall provide collimated beams and light sheets having adjustable size and position. Laser light sources used for background lighting shall be subject to the same intensity uniformity standards as the broad band background lighting sources (req. F8).

Laser light is employed in many optical measurement systems. Laser light illumination can take a variety of forms (e.g., laser light sheets, collimated beams, and point illumination of the sample). It is important that the facility architecture allow for laser upgrades to maintain the state-of-the-art capability.

It is suggested that collimated beams be adjustable up to at least 5 cm diameter, and have the capability to expand the beam up to 10 cm diameter with PI hardware.

It is suggested that the facility should be capable of generating light sheets with the following characteristics:

- Adjustable width up to 5 cm (with potential extension to 10 cm using PI hardware).
- Adjustable sheet thickness 100 to 1000 µm. Divergence of the sheet shall be minimized as much as possible (up to optical diffraction limits)
- Adjustable position translation of ±5 cm with precision of ± 0.1 mm in the chosen beam direction.

- ***Des. DF9.1***

  It is desired that FCF be capable of maintaining at least 4 lasers on orbit and have additional laser heads available for modifications and change-out. It is presumed that solid state lasers will be used whenever possible.

- ***Des. DF9.2***

  It is desired that laser heads be considered distinct and detachable from drivers for flexibility.

2.2.2 Resources (cont.)

- ***Req. F10 - Vacuum***

  FCF shall provide PI hardware access to the ISS vacuum vent system.

It is primarily intended to use this capability to create lower than ambient pressures required within some experiment test cells, for liquids/bubbles suction/collection capabilities, or for some pneumatic operations.

- ***Req. F11- Stowage***

  FCF shall provide on-orbit stowage volume having power and cooling to accommodate such needs as thermal control, stirring, and tumbling of experiment samples whenever required.

It is intended to use the stowage for:

- Experiment-specific PI hardware and supplies.
- Active experiment-specific PI experiment supplies (e.g., samples). Note that the capability to accommodate thermal control, stirring, and tumbling of the experiment samples may be required during ground ops, launch & descent, on-orbit pre & post experiment periods also.

2.2.3 Test Points and Test Duration

- ***Req. F12 - Number of Tests/ Test Durations***

  FCF shall accommodate the quantity of test points and test point durations of the fluid physics basis experiments per the estimates in figure F12. Figure F12 is a graphical statement of the requirements to be enveloped.

The basis experiments are expected to involve 10 to 500 test points of varying duration. The actual number of test points, however, will be defined and justified in the individual Science Requirements Documents. The basis experiments exhibit test point duration nominally from 1 minute up to 30 days. The test point duration reflects the length of one test point run only. It does not include factors such as experiment setup times, and change-out requirements.

Also shown are total experiment duration lines (3 days, 1 month, and 3 months) based on the duration of a test point times the quantity of test points for the experiments.

The facing figure indicates the ranges of test point quantity and test duration estimated for the basis experiments.

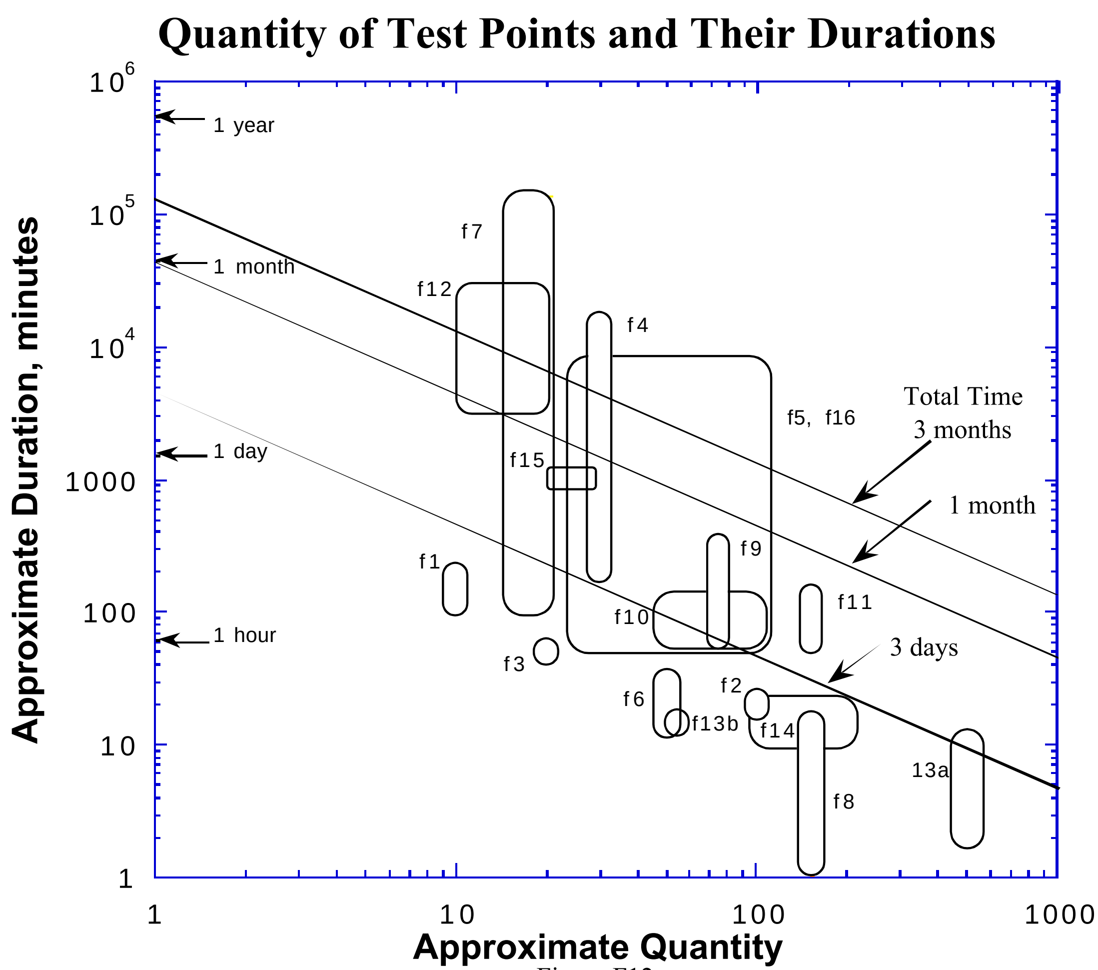

Quantity of Test Points and Their Durations
Approximate Duration, minutes
Approximate Quantity
1 year
1 month
1 day
1 hour
Total Time
3 months
1 month
3 days
f7
f12
f4
f5, f16
f15
f9
f1
f11
f10
f3
f6
f2
f13b
f14
13a
f8
1
10
100
1000
10^4
10^5
10^6

Figure F12

2.3 EXPERIMENT MEASUREMENT CAPABILITIES

The requirements discussed in this section pertain to selected measurement tools and measurement ranges called out in the basis experiments.

The following parameters are presented below in terms of requirement envelopes that are defined by the basis experiments included in this document.

- **Imaging Capabilities (2.3.1):** The facility must provide the capabilities for basic imaging and photographic documentation of the experiments.
- **Optical Interfaces (2.3.2):** The facility must provide an accessible and stable platform for implementing required optical measurement systems.
- **Optical Measurements (2.3.3):** The facility must provide measurement capabilities that accommodate the range of requirements called out in the basis experiments.
- **Analog Measurements (2.3.4):** The facility must provide necessary capabilities for making typical measurements of analog sensors (e.g., temperature, pressure, force, and voltage)

The following is a list of the requirements in this section that relate to Experiment Measurement Capabilities:

2.3.1 - Imaging Capabilities

Req. F13 Imaging Systems

2.3.2 - Optical Interfaces

Req. F14 Number of Views

Req. F15 Optics Positioning and Locating

2.3.3 - Optical Measurements

Req. F16 Field of View vs. Resolution

Req. F17 Particle Speed vs. Field of View

Req. F18 Frame Rate vs. Experiment Duration

Req. F19 Communications, LOS

Req. F20 FCF Provided Diagnostics

2.3.4 - Analog Measurements

Req. F21 Temperature Measurements

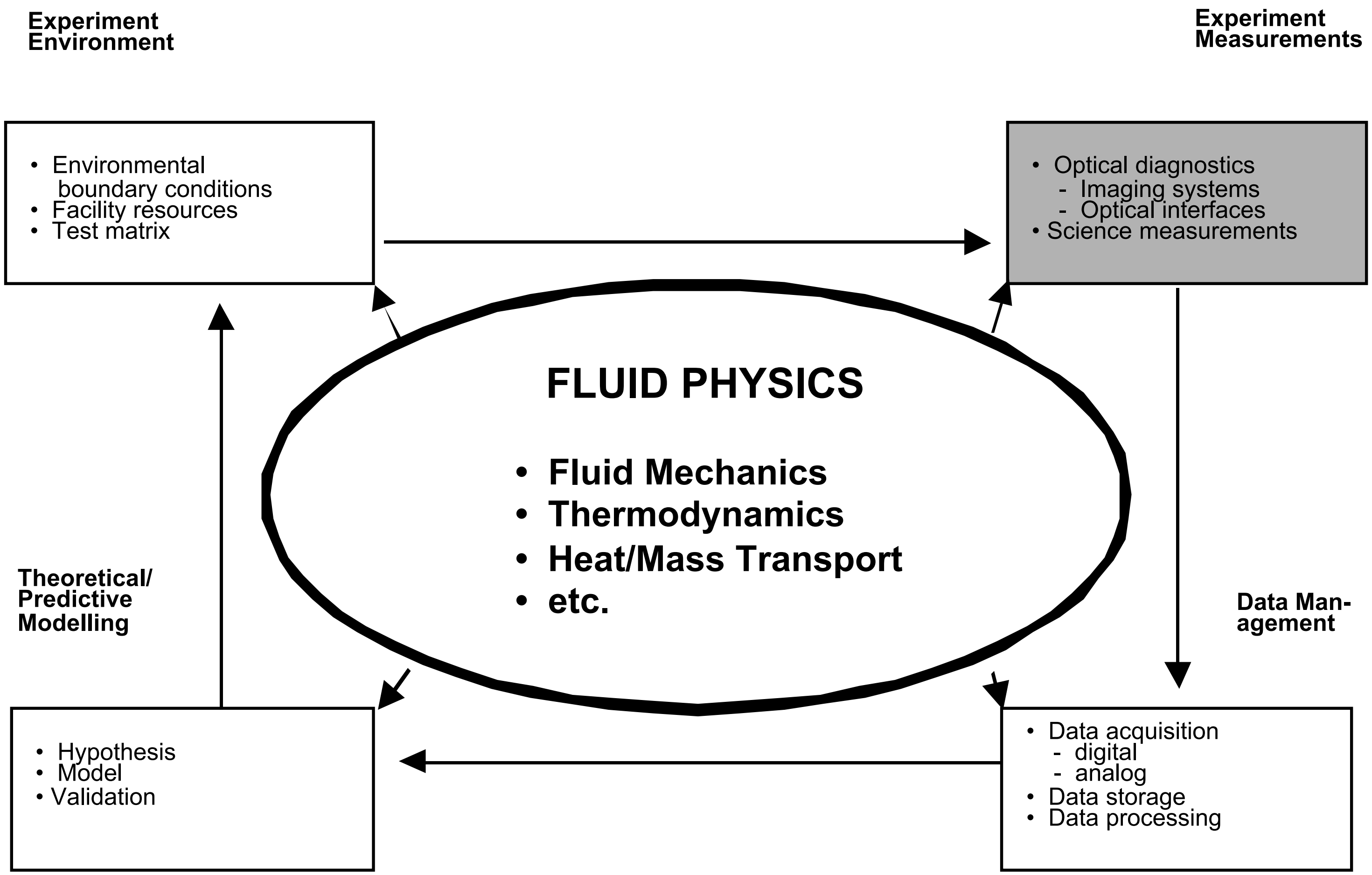
Req. F22 Presssure Measurements

Req. F23 Force Measurements

Req. F24 Voltage Measurements

Facing figure illustrates the experimental process previously shown with the Experiment Measurements (this Section 2.3) highlighted. All requirements related to these measurements are in this section.

Experiment Process Model



2.3 EXPERIMENT MEASUREMENT CAPABILITIES (cont.)

2.3.1 Imaging Capabilities

- ***Req. F13 - Imaging Systems***
- ***Req. F13.1***

  FCF shall provide a set of imaging capabilities (e.g., subassemblies incorporating cameras, lenses, mirrors, et al) covering, nominally, the entire visible light spectrum. They shall be the types and quantities required by the basis experiments.

- ***Req. F13.2***

  FCF shall accommodate PI-provided cameras and supporting hardware which are compatible with power, data acquisition, and work volume capabilities.

Fluid Physics experiments require imaging at wavelengths between 14 µm to 390 nm.

It is expected that some experiments will require special PI hardware to meet specific imaging needs and others may use FCF supplied hardware as indicated in the following table.

It is suggested that the facility and facility-provided cameras have the following capabilities:

- All necessary accommodations (e.g., power, control, translatable data, mirrors, windows, etc.)
- Standard camera features (e.g., focus, zoom, aperture, shutter speed) will be remotely controllable on facility-provided cameras.
- Selected images (e.g., film frames for film cameras), or a sequence of images can be downlinked to the PI team in near real time.
- Multiple cameras can be operated concurrently as required by the basis experiments.
- GMT or MET type time information can be embedded in image files. For example, these times would be used to correlate accelerometry data with image data.
- Quick connects will be used for control, data, and power line cables for PI specific cameras.

Flexible camera placement. In other words, camera locations can, in principal, be anywhere in the work volume, as required by the experiment. The table on the facing page summarizes the types of cameras envisioned for the fluid physics facility. Note that some will be provided by the facility and some will be provided as PI hardware. The facility shall be designed to readily accommodate the PI-provided cameras.

Recommended Camera Systems for Fluid Physics

Camera Types	Ultraviolet Light	Visible Light Monochromatic	Visible Light Color	Infrared Light
Analog video		PI	FCF	
Digital video	PI	FCF (2 cameras)	PI	PI
Cinematic		PI		
Digital stills		PI	PI	
Film-based stills		PI		

FCF = suggested as facility-provided PI = suggested as PI-provided

2.3.2 Optical Interfaces

- ***Req. F14 - Number of Views***
- ***Req. F14.1***

  FCF shall accommodate simultaneous imaging of the test cell from at least two orthogonal directions as required by the basis experiments.

There may be different frame rate and magnification requirements for each view. There will be cases in which each view will require a different diagnostic (e.g., normal/zoom visual CCD, and interferometry), and there may be situations requiring two simultaneous, but differently located, imaging zones.

- ***Req. F14.2***

  FCF shall provide downlink for at least two imaging channels in near real time with frame rate and resolution adequate to monitor the progress of the test point, for image analysis, and for interactive control of the basis experiments.

Near-real time for images is defined as less than 15 seconds after the event that was imaged. For some experiments, it may be acceptable to downlink a subset of all the images captured (e.g., every 100^{th} image or an image every 15 seconds). Compressed images are not precluded by this requirement, provided that they have adequate resolution and color depth to meet SRD requirements.

- ***Des. DF14.1***

  It is desirable to have at least two viewing directions be accessible with zoom capability.

- ***Des. DF14.2***

  It is desirable to have images of directly opposite views; e.g., front and rear view of an object should be accessible.

- ***Des. DF14.3***

  It is desirable to have ability to image two orthogonal views side by side with the same camera.

This desire implies the use of mirrors and lenses to direct the two views onto the same imaging media.

2.3.2 Optical Interfaces (cont.)

- ***Req. F15 - Optics Positioning and Locating***
- ***Req. F15.1***

  FCF shall provide positioners, optical systems, power control, and procedures to reproducibly position and align light sources, optics, and other experimental components located within the dedicated fluid physics volume. The relative positions of components shall be reproducible and knowable with the accuracy and precision required by the majority of basis experiments.

It is suggested that positions be measurable in a standard 6 degree of freedom coordinate system (e.g., x, y, z, θ, etceteras).

It is expected that any item installed in the facility by the crew on the optical bench will be coarse-aligned to specific reference points, and that a mechanism for coarse-alignments (made by the crew) will be provided by the facility. It is suggested that coarse alignment position coordinates (relative to a standard reference point) be reproducible and knowable with an accuracy of 2mm and 2 degrees if the PI experiment & hardware both requires and supports such accuracy.

- ***Req. F15.2***

  Position and alignment adjustment of PI-provided optical components with a precision of approximately a micron or less relative to other optical components shall be supported by the FCF system, as required for practical implementation of the basis experiments.

Final relative positioning with tenths of a micron precision will be needed to meet the requirements of some experiments; however, it will not be required to know the absolute position with micron scale accuracy.

It is suggested that FCF provide optical rails, x-y-z positioners, and x-z-θ positioners on the optical bench surfaces to facilitate precise alignment (relative to each other and the test cell) of FCF and PI-provided optical components.

2.3.3 Optical Measurements

The following three requirements deal with the field of view, resolution, frame rate, and duration of recording. These requirements result from considerations of diagnostic techniques such as particle imaging velocimetry (including the use of liquid crystals as particles), interferometry, and infrared imaging. These are used to map velocities, temperature and concentration profiles and fields.

- ***Req. F16 - Field of View vs. Resolution***

  FCF imaging shall accommodate the ranges of field of view and resolution necessary to support the basis experiments per the estimates in figure F16. Figure F16 is a graphical statement of the requirements to be enveloped.

The accompanying figure shows that the basis experiments exhibit fields of view from 20 x 200 microns to 30 x 40 cm and resolutions from 0.5 to 1000 µm, respectively.

It is expected that the FCF will support an envelope of optical resolutions that can be considered in different ways.

- Absolute optical resolution down to approximately 3µm (measured at the object)
- Linear resolution down to approximately 1/1000 of the longest dimension of FOV on the imaging media (e.g. film or digital camera sensor)
- FOV absolute dimensions (at the object) up to 10 x 10 cm (and preferably as large as 30 x 40 cm).

Note on experiment f1, f2: Resolutions are below the optical limit. The desired resolutions would be achieved by interferometric or other diagnostic techniques provided by PI hardware.

The facing figure shows the distribution of image resolution and fields of view that define this requirement envelope. The graph shows that most of the data lies at a ratio of field of view to resolution of 1000 or less.

Field of View Versus Resolution

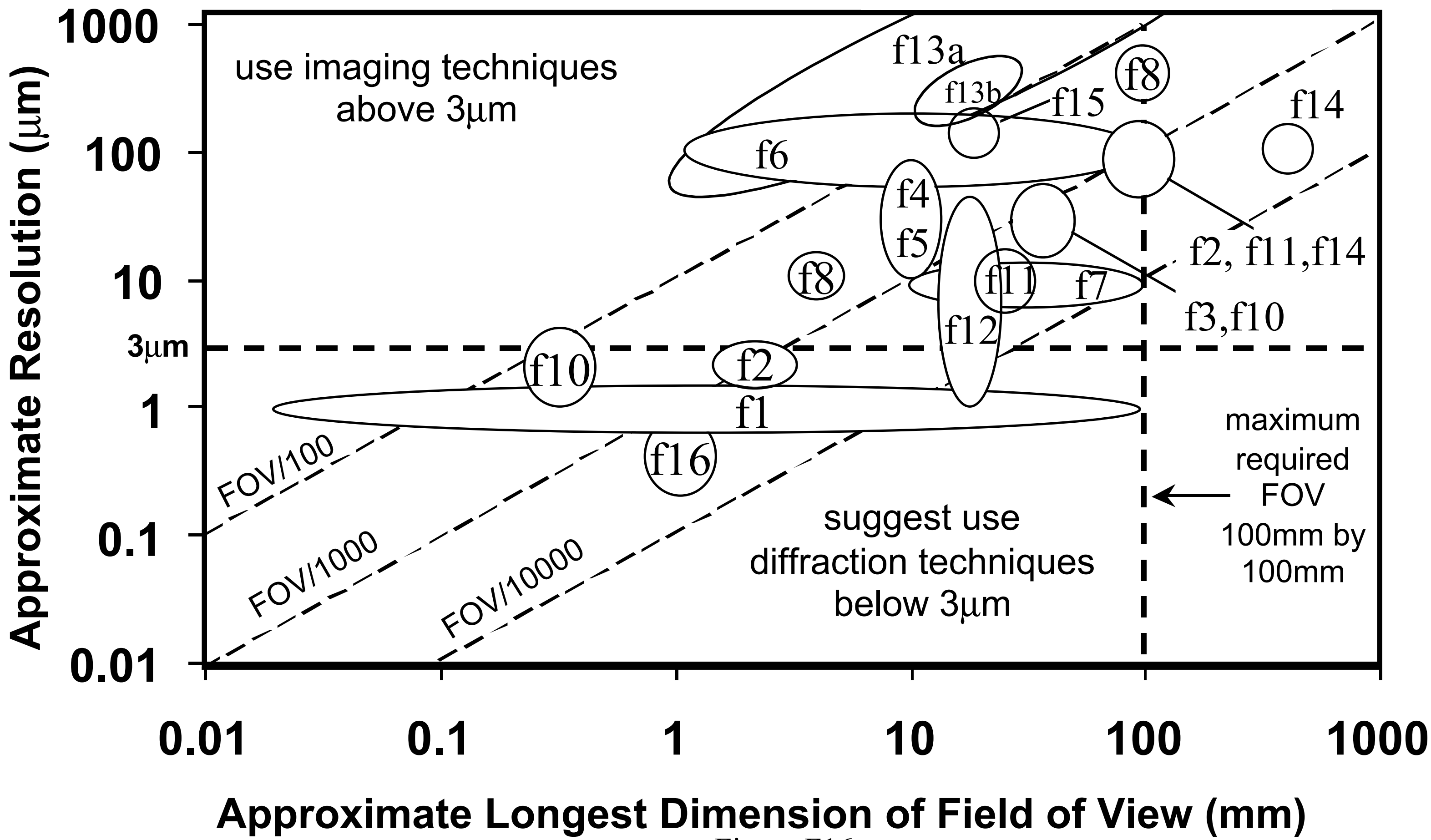


Figure F16

2.3.3 Optical Measurements (cont.)

- ***Req. F17 - Particle Speed Versus Field of View***

  FCF shall accommodate the range of fields of view (FOV) and expected particle velocities required by the basis experiments per the estimates in figure F17. Figure F17 is a graphical statement of the requirements to be enveloped.

Basis experiments exhibit fields of view between 20x200 microns to about 30x40 cm and particle speeds from 200 microns/sec to 10 m/sec.

To obtain sharp images, it is expected that the facility shall provide effective exposure times to adequately freeze particles (or objects) in motion. It is expected that the facility envelope supports FOV's up to 10 x 10 cm (and preferably as large as 30 x 40 cm) for exposure times down to 10 µs, as indicated in the following figure.

In the following figure, it is assumed that events can be frozen by allowing a maximum translation of 0.1% of field of view; then, the resulting exposure time, t, is in the 1/100 to 1/100,000 sec range.

The facing figure shows the distribution of particle speeds and fields of view that define this requirement envelope.

Exposure Duration (t) as a Function of Particle Speed

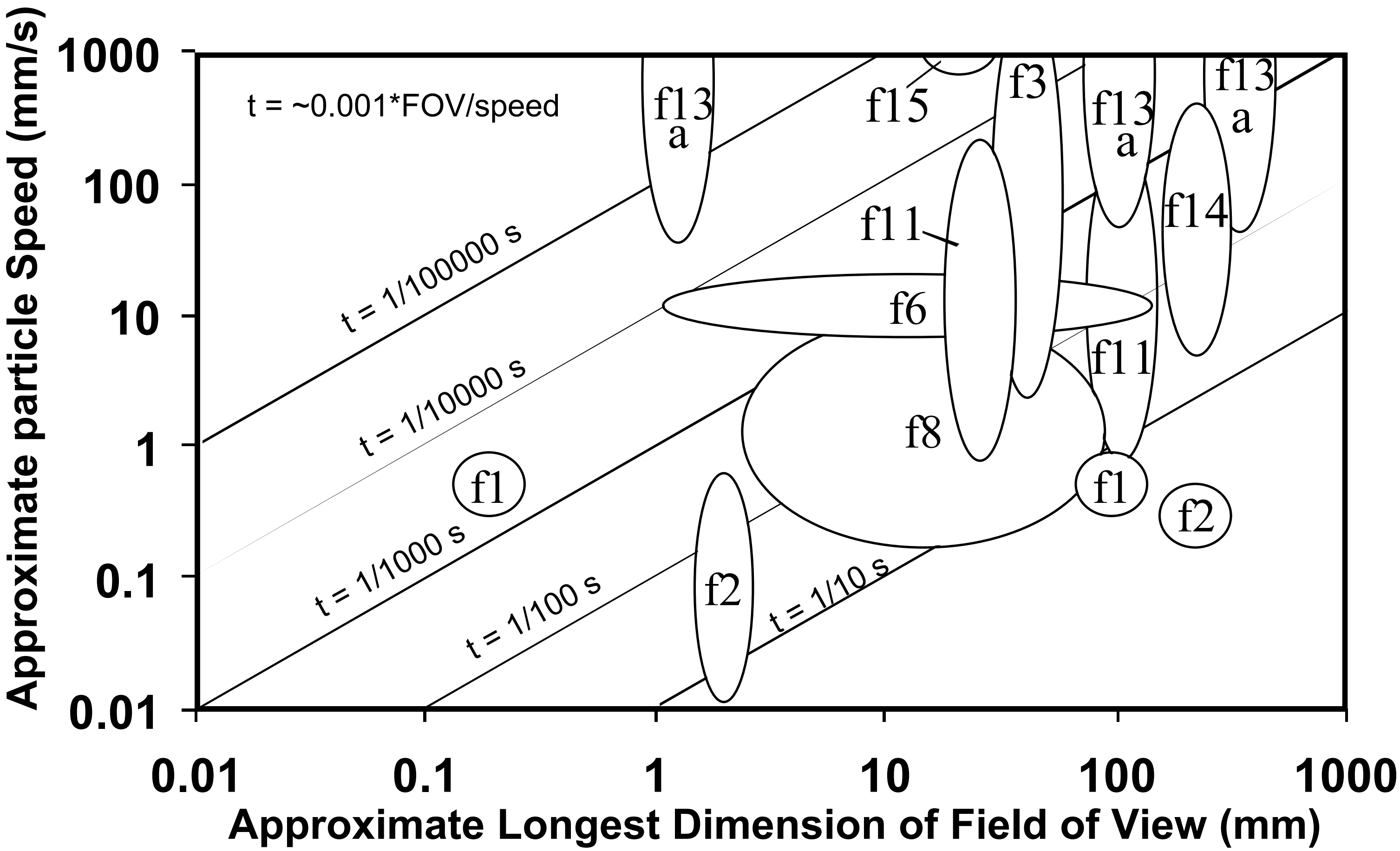


Figure F17

2.3.3 Optical Measurements (cont.)

- ***Req. F18 - Frame Rate Versus Experiment Duration***

  FCF shall provide the range of framing rate and range of quantities of images required by the basis experiments per figure F18. Figure F18 is a graphical statement of the requirements to be enveloped.

Basis experiments exhibit frame rates ranging from one frame every several minutes to 1000 fps and recording durations from 5 to 2000 seconds per experiment run. Therefore, it is expected that the facility envelope includes frame rates up to 1000 fps, and it is expected that at least 8 Gigabytes of image storage per camera per data point run will be available.

The facing figure shows that generally higher frame rates are required for shorter duration, and that the estimated total number of frames is less than about 50,000 for any one experiment run. Also, in experiment f10, some cases will require 6 minutes between frames (time-lapse mode). In experiment f12, only a smaller subset (up to 20 seconds) of the 5 minutes at 200 fps would be of interest, and the point on the x-axis represents taking occasional pictures. In experiment f13, it is desirable to have up to 300 x 512 pixels at 1000 fps for 15 minutes.

- ***Des. DF18.1***

  It is desired that the facility not preclude higher camera frame rates (e.g., 2000 fps).

The facility frame rate capability should increase as higher speed cameras and higher capacity storage devices become available. It is desired that the facility be scarred to make easy, low cost upgrade feasible.

It is suggested that the facility provide a capability to variably select an area of interest (AOI) within the field of view for recording purposes (e.g., a 60 x 40 pixel array). This capability could increase the duration of recording of smaller AOI's at the highest fps.

It is suggested that the facility allow images to be stored in both uncompressed and compressed formats (with the level of compression being selectable).

The facing figure shows the distribution of frame rates and recording duration that define this requirement envelope.

Recording Duration For Various Framing Rates

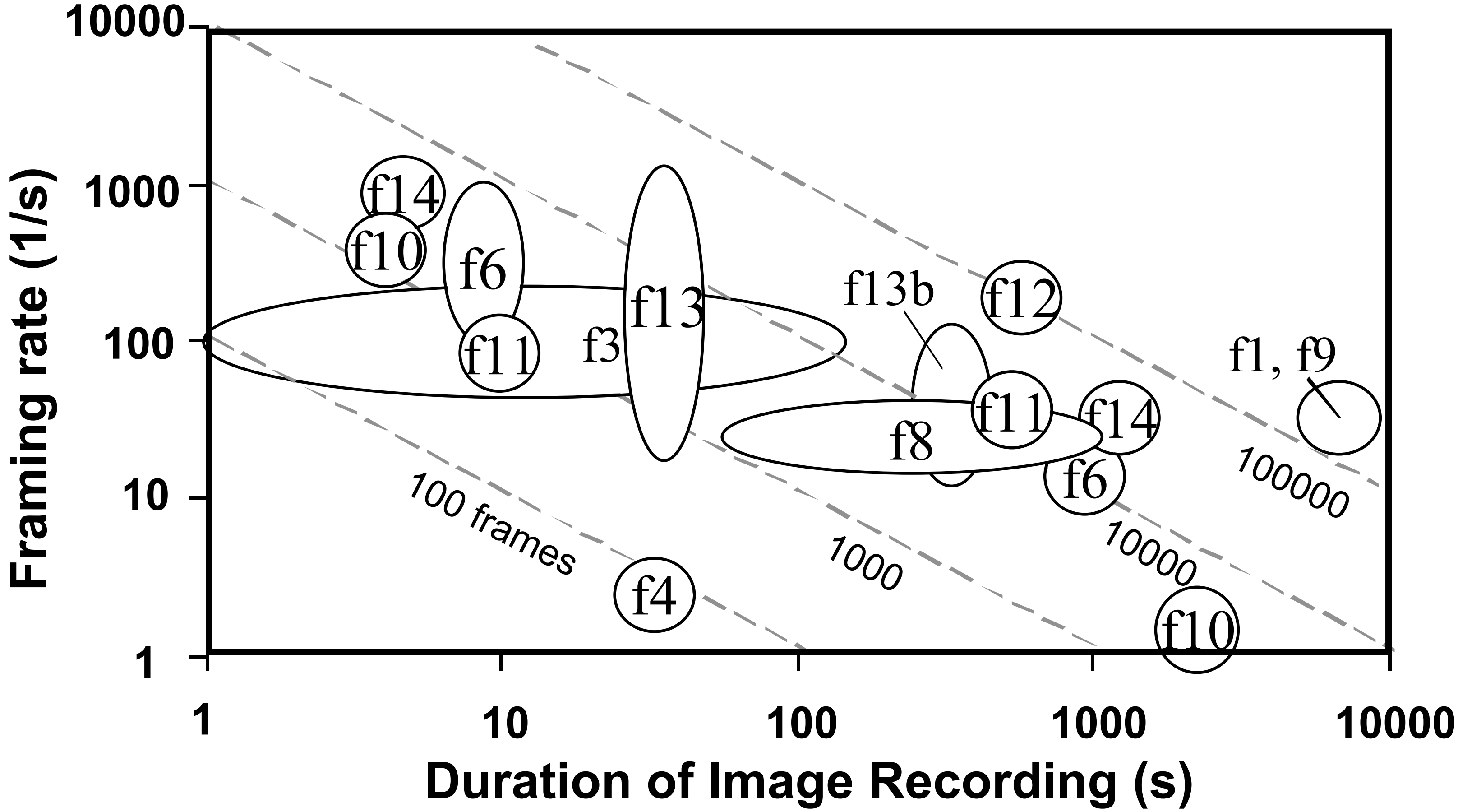


Figure F18

2.3.3 Optical Measurements (cont.)

- ***Req. F19 – Communications, LOS***
- ***Req. F19.1***

  FCF shall provide at least one removable media recording device capable of recording the equivalent of 2 hours of standard video data.

The term ‘standard video data’ is defined as equivalent to current (cy 1998) commercial SVHS video standards. Image compression could be used, if the images retain the quality of current SVHS video. The removable media would be played back while still on board or returned to earth, if required by a given experiment.

- ***Des. DF19.1***

  Continuous communication between the experiment ground operations team and the facility is highly desirable.

Communications should be possible for at least 67% of every orbit during data point runs. It would be used to send commands, receive instrumentation data, and image data.

- ***Req. F20 – FCF Provided Diagnostics***
- ***Req. F20.1***

  FCF shall provide diagnostics commonly needed by Fluid Physics experiments.

These diagnostics will include a variety of optical measurement capabilities comparable to the Earth-based laboratory diagnostics used by the Principal Investigators. This is to prevent the need for each PI team to “reinvent” commonly used diagnostics.

- ***Des. DF20***

  It is desired that FCF provide the following optical diagnostic capabilities as FCF supplied hardware and software per the recommendations in table DF20:

  DF20.1 General Video Imaging

  DF20.2 Video Microscopy

  DF20.3 Static Light Scattering

  DF20.4 Dynamic Light Scattering

  DF20.5 Shadowgraphy

  DF20.5 Particle Image Velocimetry

  DF20.6 Shearing Interferometry

  DF20.7 Surface Profilometry

All recommended capabilities are not required to be implemented with the initial deployment of the Fluid Physics rack.

The facing table presents a list of optical diagnostic techniques which is recommended for inclusion into FCF.

RECOMMENDED OPTICAL DIAGNOSTICS

DIAGNOSTIC TECHNIQUE	BASIS EXPERIMENT	RECOMMENDED BASELINE CAPABILITY	RECOMMENDED UPDATED CAPABILITY
General imaging	f1 to f16	multiple views, zoom capability, particle tracking, color and b&w, frame rates to 300 per sec	high frame rates (to 2000 per sec)
IR imaging	f1, f11		as required
Video microscopy	f1, f2, f10, f15,f16	2 views	
Static and dynamic light scattering	f4, f5, f7, f12, f16	required	
Shadowgraph	f11	required	
Schlieren			as required
Color schlieren			as required
Particle image velocimetry	f1, f2, f3, f10, f11	required	
Laser induced fluorescence	f10		as required
Mach-Zehnder interferometry	f8, f9, f12		as required
Michelson interferometry	f1, f12		as required
Twyman-Green interferometry	f12		as required
Point diffraction interferometry	f8, f9		as required
Shearing interferometry	f1, f8 f9, f12, f14	required	
Liquid crystal point diffraction interferometry	f8, f9		as required
Laser feedback interferometry	f1		as required
Surface profilometry	f11	required	
Ronchi (surface slopes measurement)	f11		as required
Laser Induced Photochemical Anemometry			as required
Confocal and fluorescence microscopy	f16		as required
Laser tweezers	f16		as required
Spectrophotometry	f16		as required
Spectroscopy: DTS, DWS	f15		as required

2.3.4 Analog Measurements

The following requirement pertains to measurements of temperature, pressure, force, torque, stresses, voltage, current, magnetic field, linear and angular positions, and translational and rotational speeds inside PI hardware. Such measurements usually transform to measurement of voltages from the various transducers. Normally, the transducers will be provided as part of the PI hardware. [The sampling rates and storage capabilities are summarized in Section 2.4 in terms of data management.]

- ***Req. F21.1 - Temperature Measurements***

  FCF shall be capable of accommodating acquisition and storage of temperature data from a variety of transducers at various ranges, precisions, and data rates per the estimates in figures F21a, F21b, and F21c. Figures F21a, F21b, and F21c are a graphical statement of the requirements to be enveloped.

- ***Req. F21.2 – Temperature Instrumentation***

  FCF shall identify temperature measurement instruments or techniques appropriate to the needs of the basis experiments (as implied by figures F21a, F21b, and F21c) and verify their performance in FCF systems. The transducer specifications, test information and, samples shall be made available to PI hardware developers.

Temperature: Most of the temperatures expected range about ambient conditions. Experiments f8, f9, and f13 require temperatures ranging from about -20 to 120°C.

Facing figure indicates ranges of temperature measurement rates and duration required by the basis experiments.

Temperature Measurement Rate and Duration

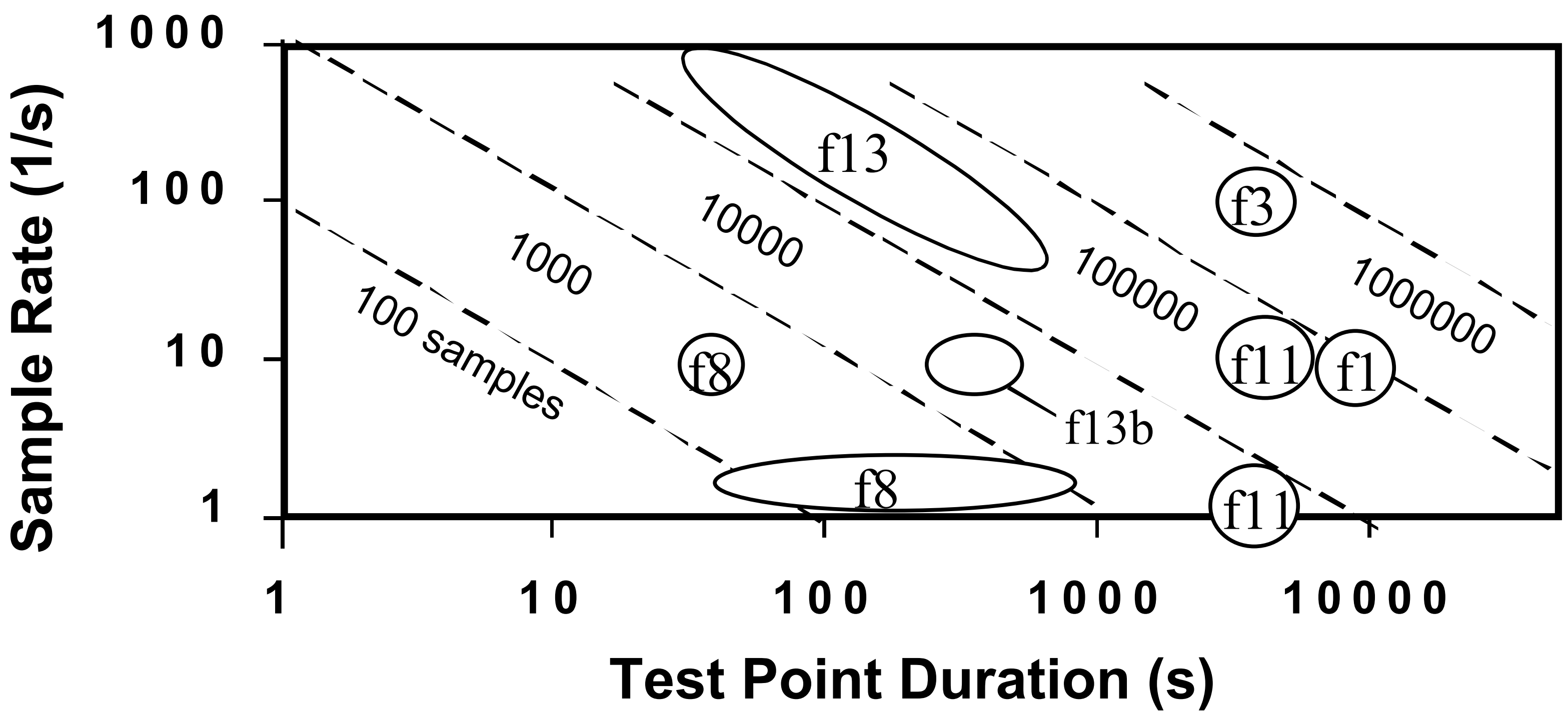


Figure 21a

2.3.4 Analog Measurements (cont.)

Figure on facing page shows the ranges of precision point temperature measurement called out by the basis experiments.

Point Temperature Measurement Precision

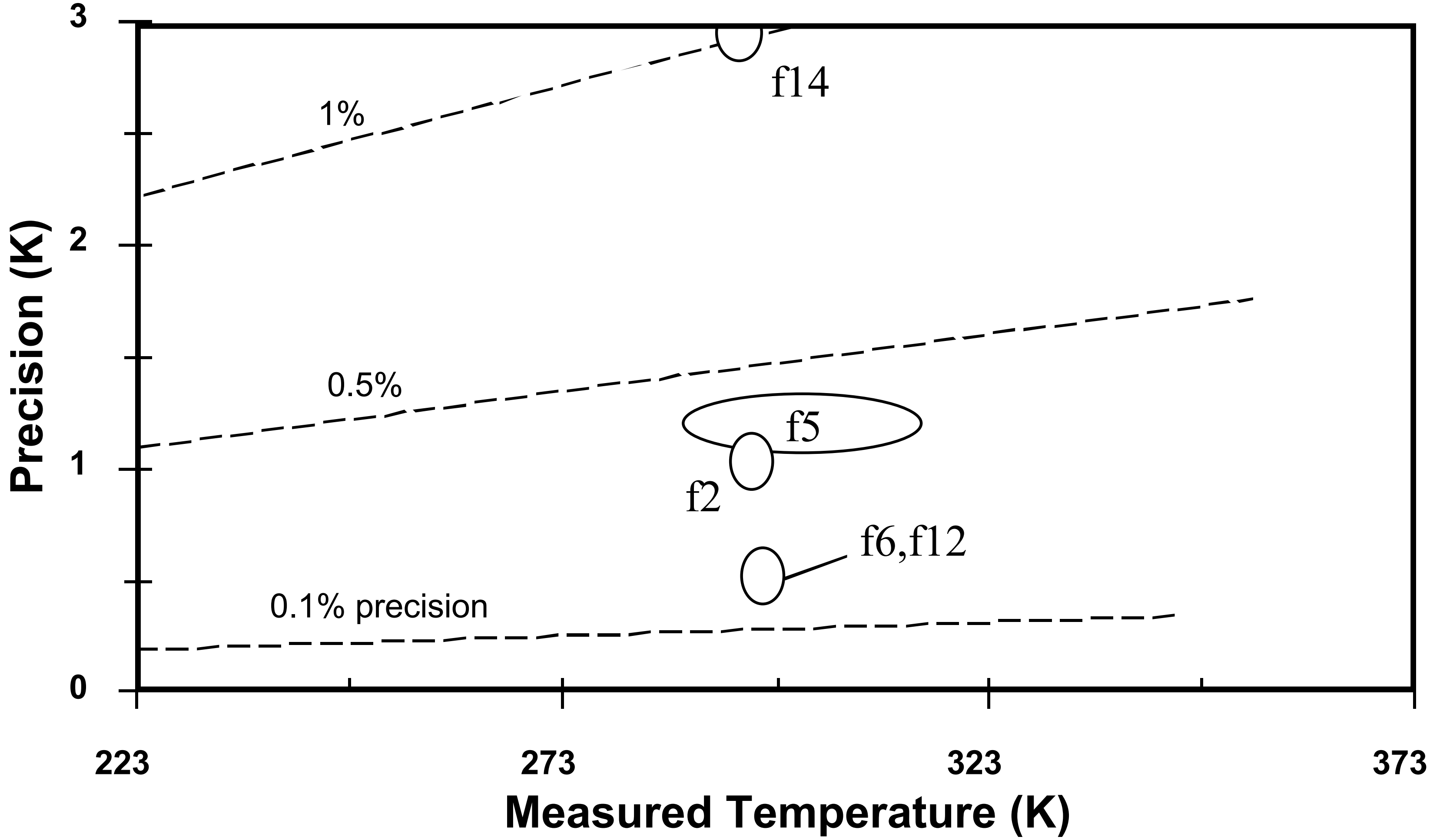


Figure 21b

2.3.4 Analog Measurements (cont.)

The facing figure indicates the temperature measurement precision required by the basis experiments.

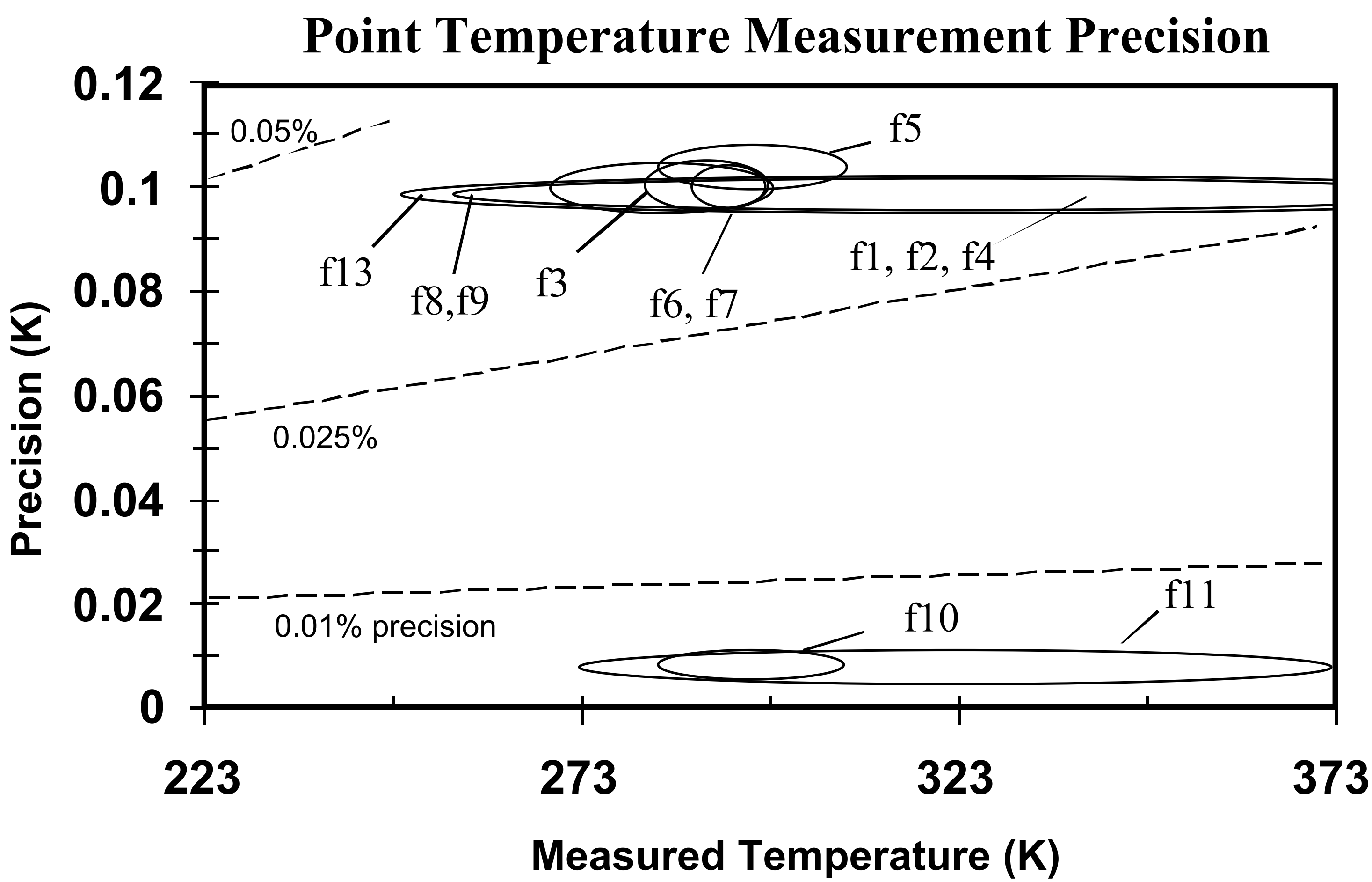

Point Temperature Measurement Precision
0.12
0.1
0.08
0.06
0.04
0.02
0
Precision (K)
0.05%
f5
f13
f8,f9
f3
f6, f7
f1, f2, f4
0.025%
0.01% precision
f10
f11
223
273
323
373
Measured Temperature (K)

Figure 21c

2.3.4 Analog Measurements (cont.)

- ***Req. F22.1 - Pressure Measurements***

  FCF shall be capable of accommodating acquisition and storage of pressure data at various ranges, precisions, and data rates per the estimates in figures F22a and F22b. Figures F22a and F22b are a graphical statement of the requirements to be enveloped.

- ***Req. F22.2 – Pressure Instrumentation***

  FCF shall identify pressure measurement instruments or techniques appropriate to the needs of the basis experiments (as implied by figures F22a and F22b) and verify their performance in FCF systems. The transducer specifications, test information, and samples shall be made available to PI hardware developers.

Pressure: These measurements, typically, need to be taken to within 0.1%; pressures for the multiphase flow experiments run from atmospheric to several hundred psia. Most other experiments are done at one atmosphere and measurements are nominal.

Facing figure shows the ranges of pressure measurement sample rate, precision, and pressure required by the basis experiments.

Pressure Measurement Precision

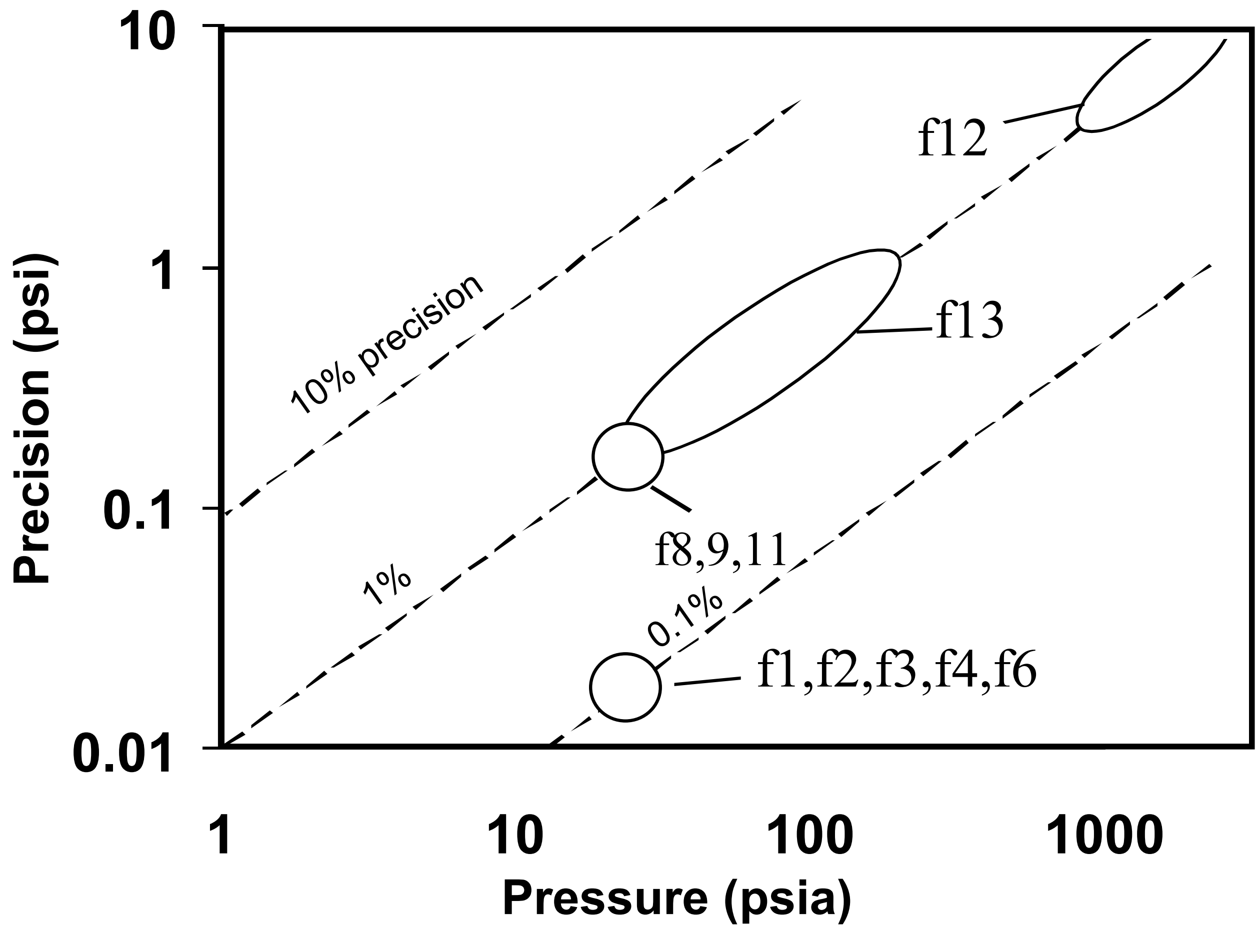


Figure 22a

2.3.4 Analog Measurements (cont.)

The facing figure indicates the quantity of pressure measurements required by the basis experiments.

Pressure Measurement Rate and Duration

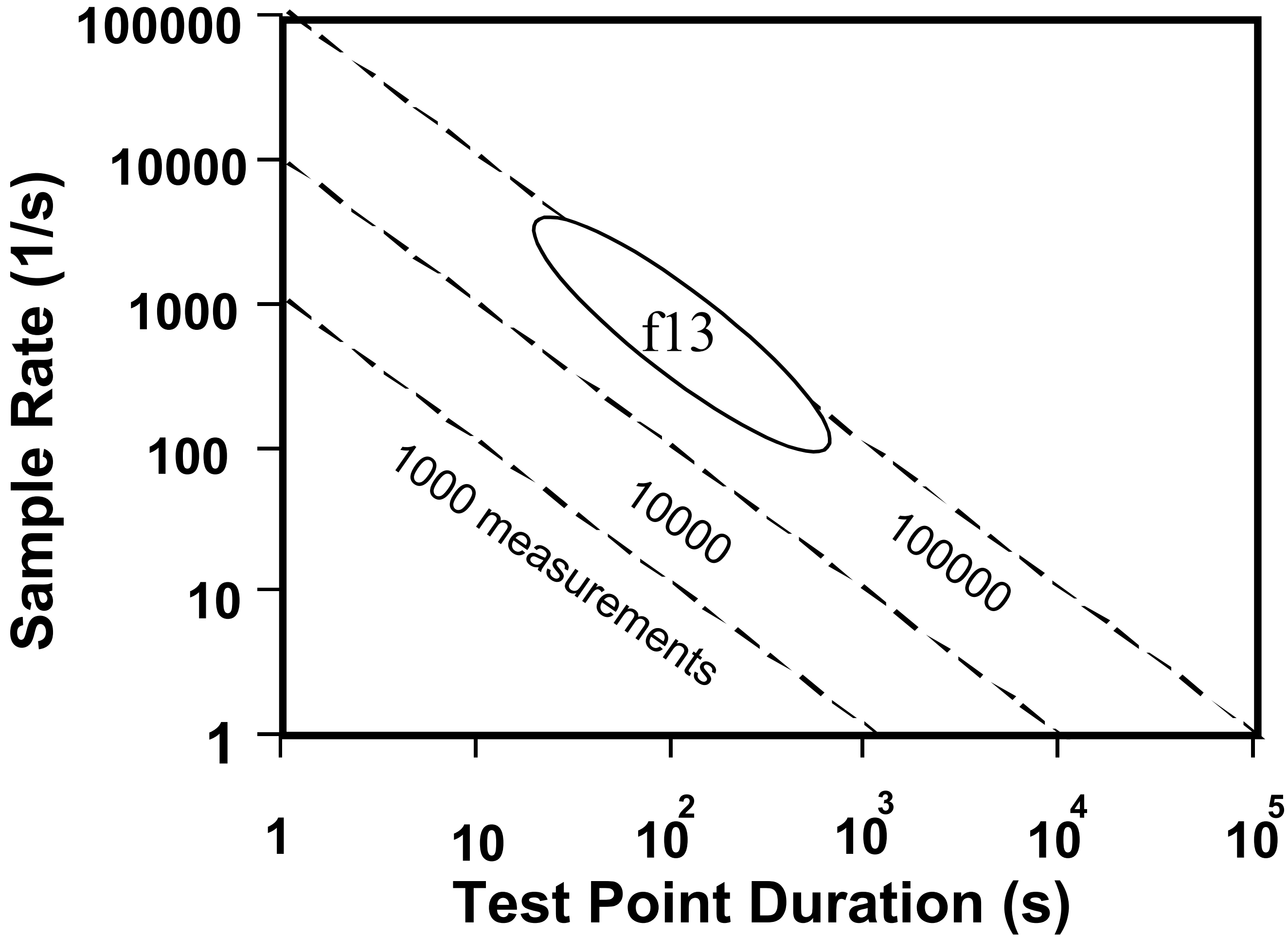


Figure 22b

2.3.4 Analog Measurements (cont.)

- ***Req. F23.1 - Force Measurements***

  FCF shall be capable of accommodating acquisition and storage of force at various ranges, precisions, and data rates per the estimates in figures F23a and F23b. Figures F23a and F23b are a graphical statement of the requirements to be enveloped.

- ***Req. F23.2 – Force Measurement Instrumentation***

  FCF shall identify force measurement instruments or techniques appropriate to the needs of the basis experiments (as implied by figures F23a and F23b) and verify their performance in FCF systems. The transducer specifications, test information, and samples shall be made available to PI hardware developers.

Force: For experiment f3, the force measurement ranges from 1 to 10,000 dynes at ±1 dyne, and 100 to 1,000,000 dynes at ±100 dynes.

Facing figures show the ranges of sample rate, precision, and force measurements called out by the basis experiments.

Force Measurement Precision

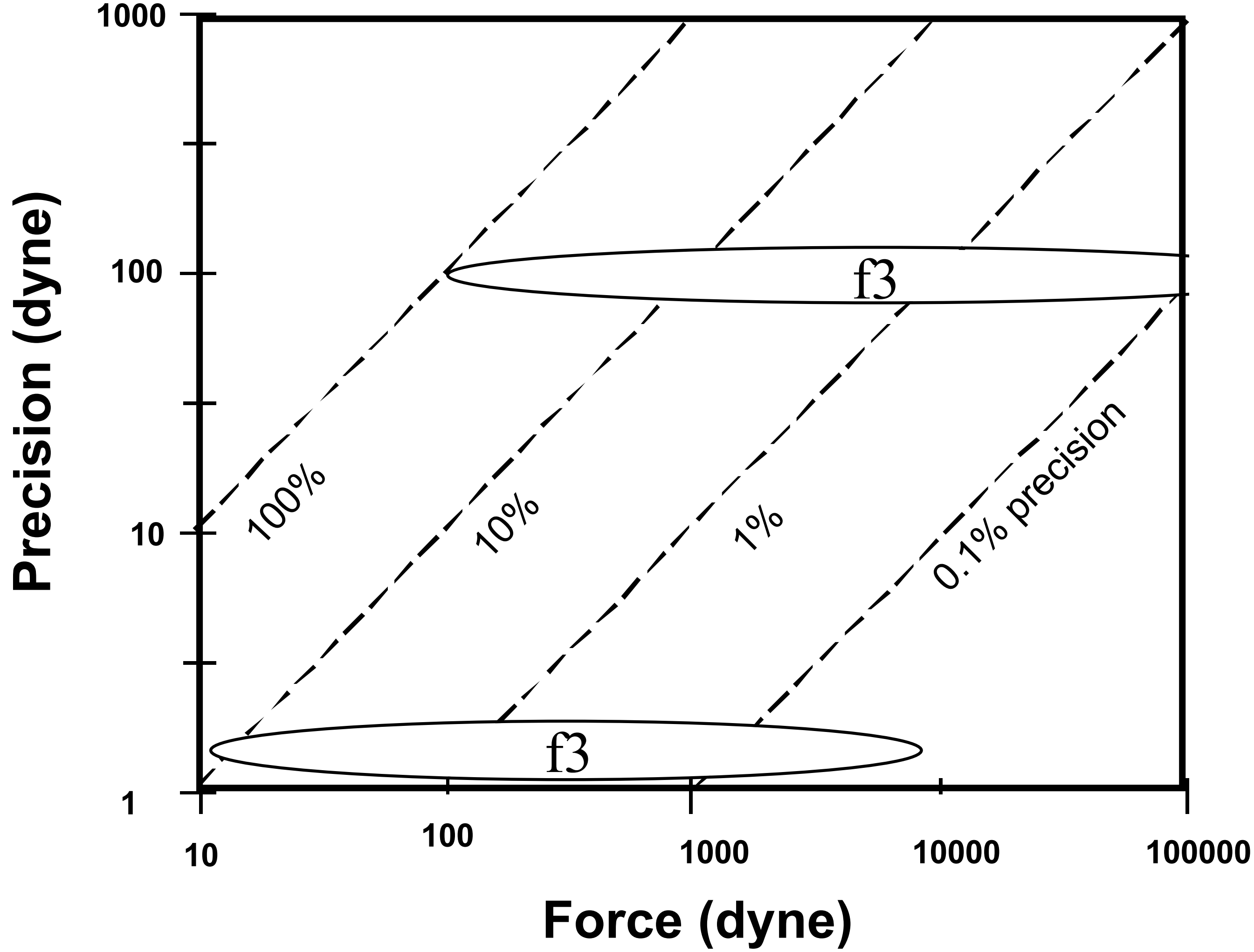


Figure 23a

2.3.4 Analog Measurements (cont.)

The facing figure indicates the quantity of force measurements required by the basis experiments.

Force Measurement Rate and Duration

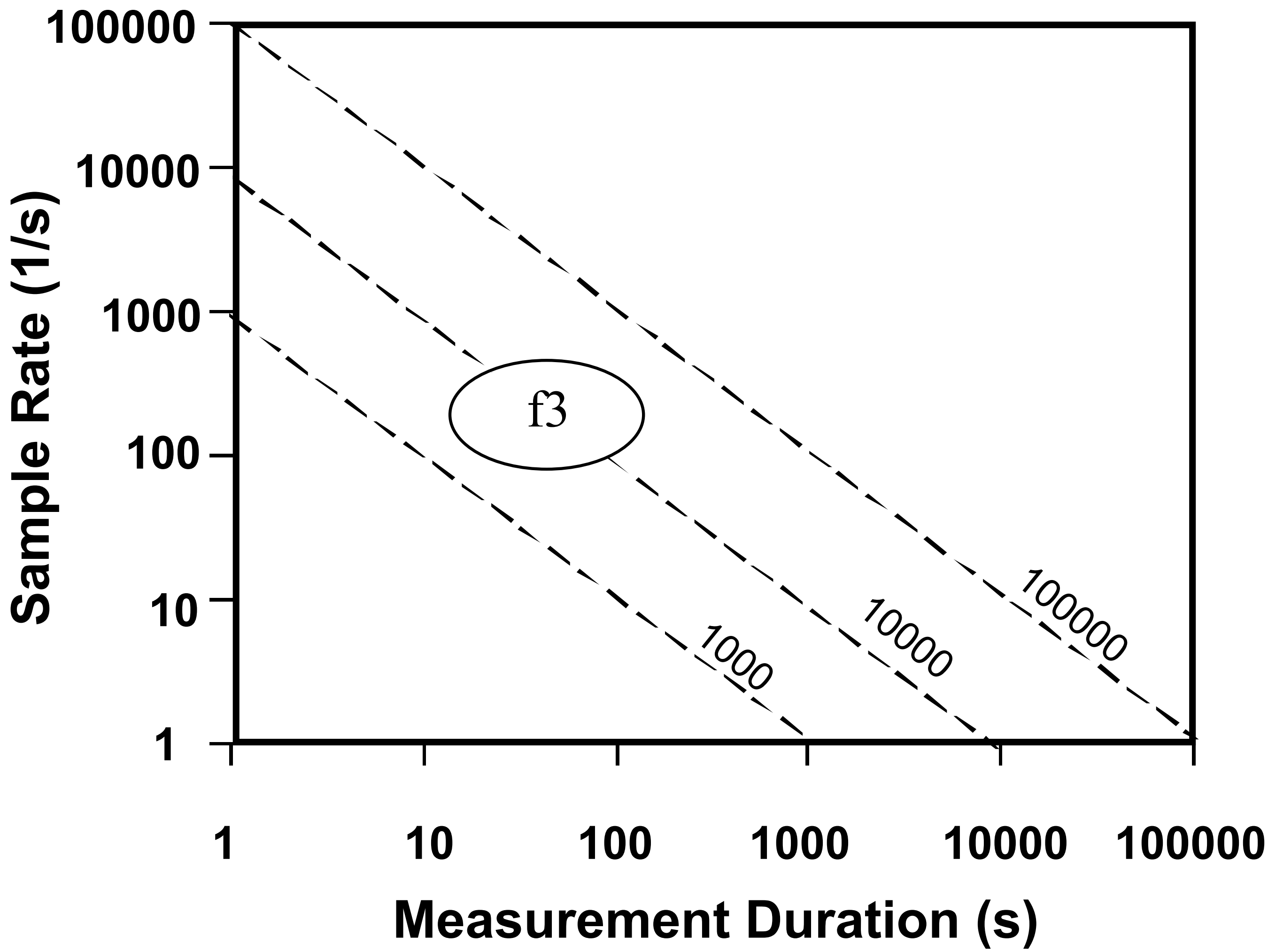


Figure 23b

2.3.4 Analog Measurements (cont.)

- ***Req. F24.1 - Voltage Measurements***

  FCF shall be capable of accommodating acquisition and storage of voltage data at various ranges, precisions, and data rates per the estimates in figures F24a and F24b. Figures F24a and F24b are a graphical statement of the requirements to be enveloped.

- ***Req. F24.2 – Voltage Measurement Instrumentation***

  FCF shall identify voltage measurement instruments or techniques appropriate to the needs of the basis experiments (as implied by figures F24a and F24b) and verify their performance in FCF systems. The transducer specifications, test information, and samples shall be made available to PI hardware developers.

Voltage: For experiment f6, the voltages range from 100 to 20,000 volts (AC and DC). These voltages are used to supply an electric field. The other voltages for experiments f12 and f13 are for resistance heaters.

Facing figures show the ranges of sample rate, precision, and voltage measurements called out by the basis experiments.

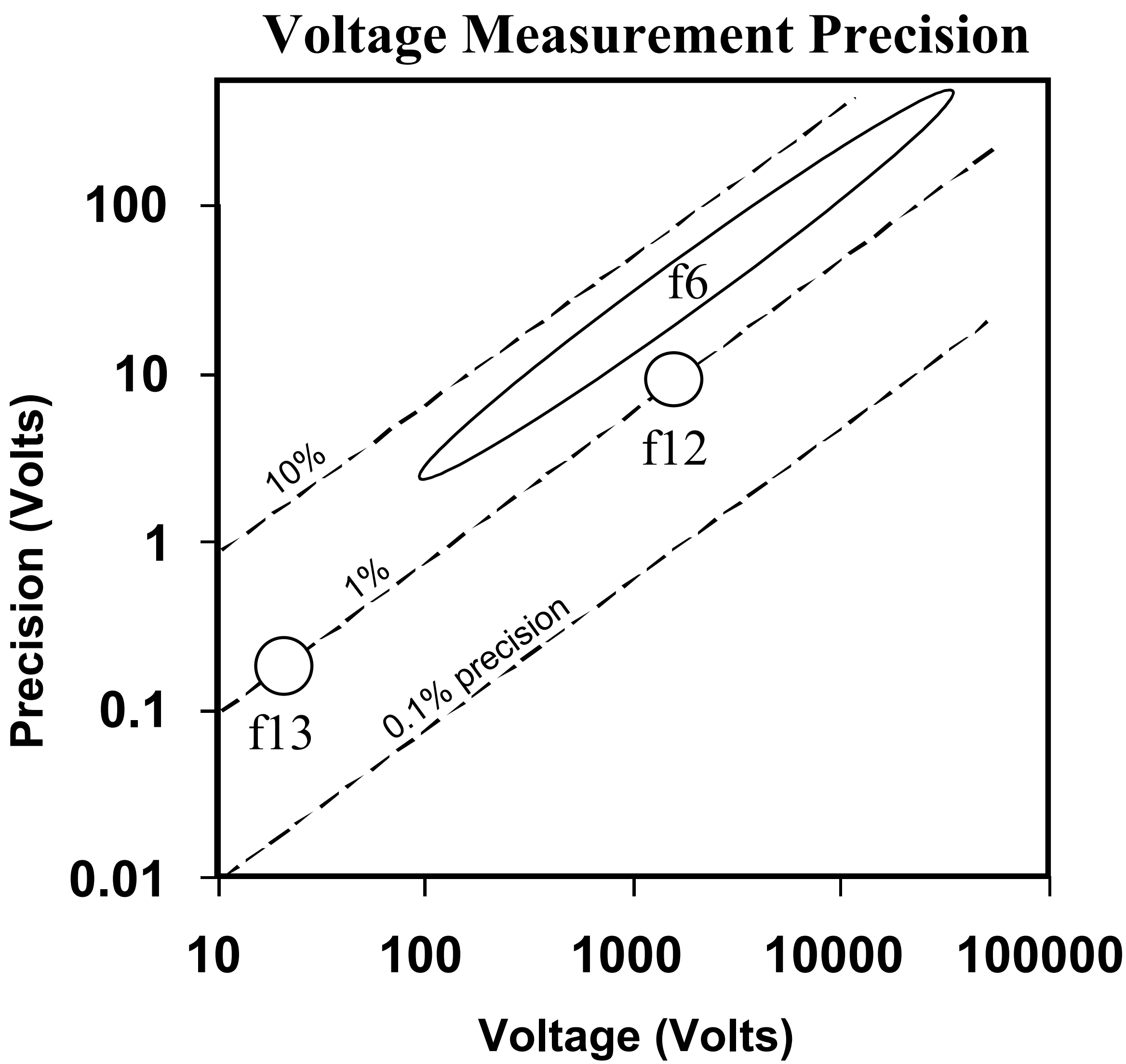

Voltage Measurement Precision
100
10
1
0.1
0.01
Precision (Volts)
10
100
1000
10000
100000
Voltage (Volts)
10%
1%
0.1% precision
f6
f12
f13

Figure 24a

2.3.4 Analog Measurements (cont)

The facing figure indicates the range of voltage sampling rate and experiment durations expected for the basis experiments.

Voltage Sampling Rate vs. Experiment Duration

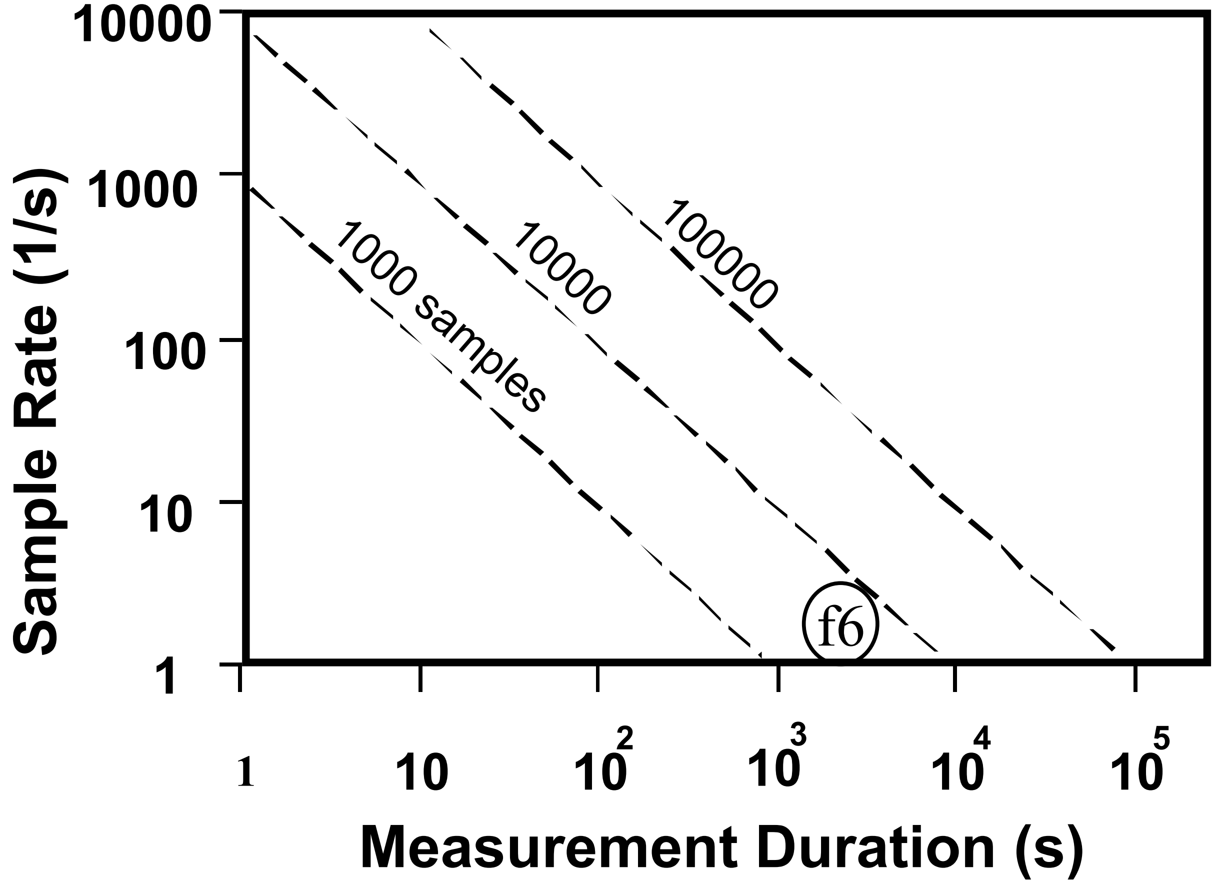


Figure 24b

2.4 EXPERIMENT DATA MANAGEMENT

The requirements discussed in this section pertain to data system capabilities.

The following parameters are presented below in terms of requirement envelopes that are defined in terms of the basis experiments included in this document.

- **Data Acquisition (2.4.1):** The facility must be capable of acquiring both analog and digital signals.
- **Data Storage (2.4.2):** The facility must provide adequate data storage to accommodate data flow of the experiments.
- **Experiment Control (2.4.3):** The facility must be capable of controlling both digital and analog devices.

The following is a list of the requirements in this section that relate to Data Acquisition and Management:

2.4.1 - Data Acquisition

Req. F25 Analog Acquisition

Req. F26 Digital Acquisition

2.4.2 - Data Storage

Req. F27 Data Recording

Req. F28 Data Time Tags

2.4.3 - Experiment Control

Req. F29 Analog Control

Req. F30 Internal/External Triggering

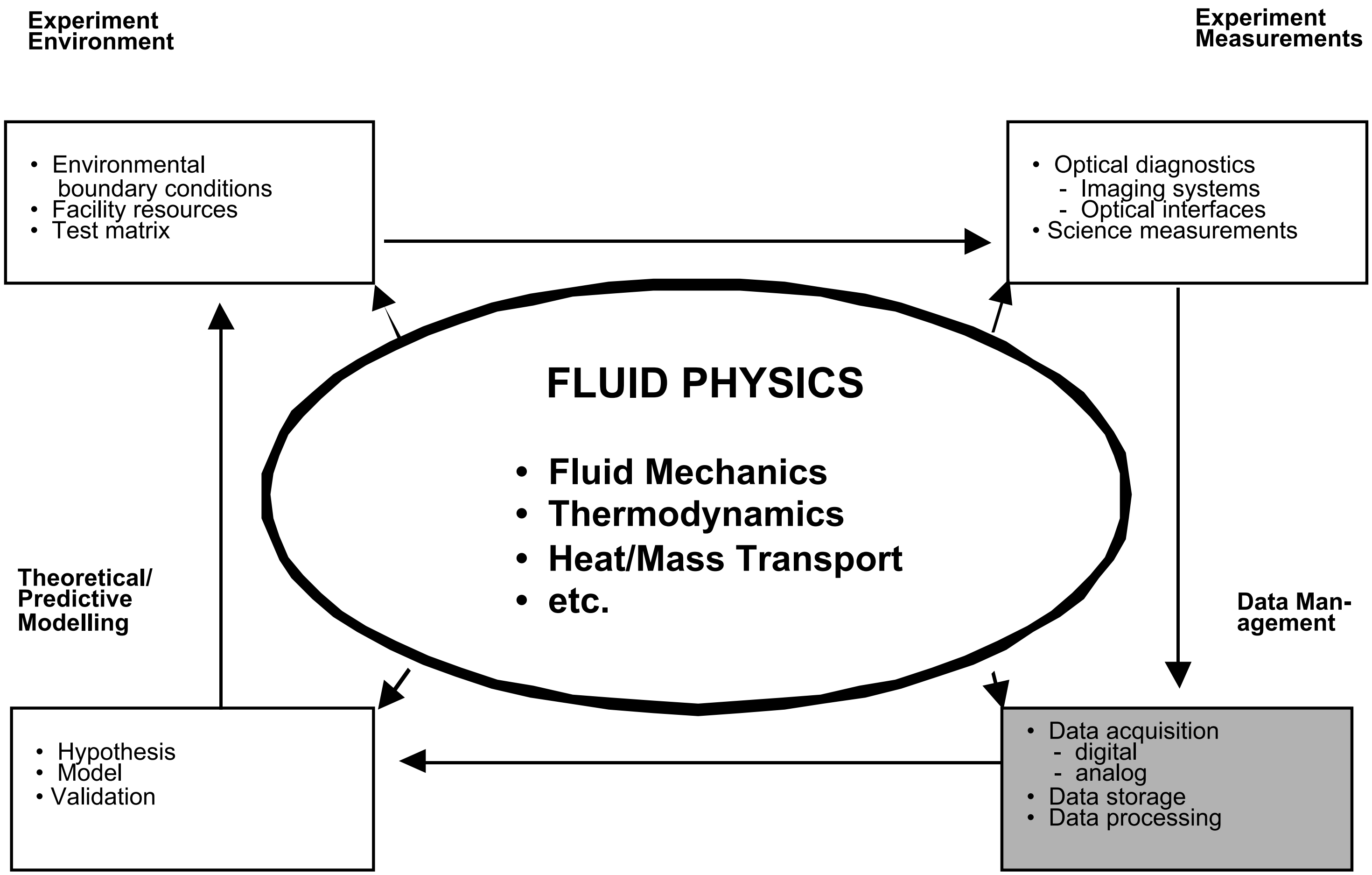
Req. F31 Digital Control

Req. F32 Experiment-Specific Capabilities

Req. F33 Image Analysis Capability

Facing figure illustrates the experimental process previously shown with the Data Management (this Section 2.4) highlighted. All requirements related to this process are in this section.

Experiment Process Model



2.4 EXPERIMENT DATA MANAGEMENT (cont.)

2.4.1 Data Acquisition

The facility shall supply an easily upgradable, flexible, modular, and "state-of-the-art" architecture for the acquiring, recording, retrieving, and transferring of data.

- ***Req. F25 - Analog Acquisition***

  FCF shall be capable of simultaneously sampling multiple channels of analog signals originating in PI hardware with sampling rates, as required to accommodate the basis experiments.

The analog data will originate in sensors provided as part of the FC or the PI hardware. FCF should provide a convenient mechanical/electrical interface between the PI hardware and FCF. The interface should minimize introduction of noise into the analog signals.

It is suggested that the system be capable of simultaneously sampling up to 64 analog channels using 16-bit A/D converters. It should provide signal integration capability, filtering, and other standard features of systems used in earth based laboratories.

A summary of data sampling rates required by the basis experiments is given below.

Sample Rates	*Experiments*
< 1 Hz	f2, f7
1 Hz – 10 Hz	f3, f5, f6, f8, f9, f10, f11, f13b, f14, f16
10 Hz – 100 Hz	f4, f8, f9, f11, f12
100 Hz – 1000 HZ	f3, f13a
>1000 Hz	f13a, f15

- ***Des. DF25.1***

  FCF should provide an analog to digital conversion system available for use by PI hardware and having as many as possible of the following characteristics.

  - Adjustable gain
  - Selectable sampling at up to 20 kHz rates with sample and hold capability
  - Monopolar or bipolar selection per channel, in order to take full advantage of the A/D dynamic range (e.g., ±1, ±2, ±5, ±10 Volts, similar for Ohms and Amps).
  - Single-ended and differential-ended types of measurement used simultaneously.
  - Equivalent resolution of 8 1/2 digits;
  - Upgradable to 256 analog channels for future use.
  - Easily interface with existing laboratory and commercial instrumentation.

The desired capabilities should be comparable to the best commercial laboratory equipment available at time of facility design.

- ***Req. F26 - Digital Acquisition***

  FCF shall be capable of simultaneously sampling multiple channels of digital signals originating in PI hardware, as required to accommodate the basis experiments.

It is suggested that at least 32 simultaneous TTL-level input channels to read digital input signals (1 bit each) at, nominally, zero to 5 volts, be provided.

2.4.2 Data Storage

- ***Req. F27 - Data Recording***
- ***Req. F27.1***

  FCF shall provide non-volatile storage for experiment-specific, non-image data (e.g., transducer readings) as required by the Basic Experiments but not less that 9 Gbytes shall be provided for the purpose.

It is expected that all the experiment data, and the experiment-related facility data are made available and stored reliably until they are analyzed or down-linked.

It is also expected that as technology improves the amount of storage may increase.

- ***Des. DF27.1***

  It is desired that all data should be recorded using standard commercial formats that can be easily accessed by PI software.

- ***Des. DF27.2***

  FCF should provide a minimum of 32 Mbyte of CPU bus speed storage (e.g., RAM) for experiment specific non-image data (e.g., transducer readings).

The desired capabilities should be comparable to the best commercial laboratory equipment available at time of facility design.

2.4.2 Data Storage (cont.)

- ***Req. F28 – Data Time Tags***
- ***Req. F28.1 - Data Time Tags***

  FCF shall provide the capability to time tag all data, including video data relative to an ISS provided timing signal. The time tag shall be of equivalent accuracy and precision to the ISS on-board timing signal or as required by the basis experiments, whichever is less stringent.

All data shall be tagged to allow correlation to an external clock provided by ISS that is presumed to be GMT. It is suggested that an accuracy and precision of 1s and 0.1s, respectively, would be appropriate.

- ***Req. F28.2***

  FCF shall provide the capability to time tag all data relative to an ISS provided clock signal and an FCF provided internal clock signal. The accuracy and precision of the time tag shall be approximately 0.1s and 0.01s, respectively.

Time tagging need not be coincident with the data acquisition if the required accuracy and precision can be maintained in tags applied after data is collected. Every data item does not need to be tagged if the items are parts of a sequence with an accurately known interval (i.e., tag one of the items and calculate the time of the others) and are synchronous within the resolution of the resolution of the master clock.

Experiment specific data streams will (potentially) be correlated to a PI-provided clock to 0.001 second using PI hardware.

Tagging each data stream will allow the PI to correlate multiple experiment measurements with experiment-specific observations and external events.

- ***Des. DF28.1***

  It is desired that FCF provide capability to tag data at selectable precision and frequency. The precision/resolution on time tagging should be consistent with the data sampling rate used.

2.4.3 Experiment Control

- ***Req. F29 - Analog Control***

  FCF shall provide multiple channels of analog output. These shall be capable of waveform generation as well as producing point voltage values. The quantity of channels, their accuracy, and their precision shall be adequate to control the basis experiments. At least 16 channels of at least 12-bit analog output shall be provided to experiments that require them.

It is expected that the capabilities include single voltage control as well as arbitrary function generation over variable and flexible voltage ranges (monopolar as well as bipolar). It is suggested that FCF provide up to 16 channels of analog output at 16 bit nominal resolution (i.e., 16 bit D/A converters).

- ***Des. DF29.1***

  It is desired that provisions be provided to increase the number of available D/A channels to 64 as demand increases.

- ***Des. DF29.2***

  It is desired that a variety of wave forms be generated at selectable frequencies to 1 MHz and selectable amplitudes.

The desired capabilities should be comparable to commercial laboratory equipment available at time of facility design.

2.4.3 Experiment Control (cont.)

- ***Req. F30 Internal/External Triggering***

  The facility shall provide internal and external triggering capability to enable the individual experiments to trigger and correlate various events.

It is expected that FCF has the ability (hardware and software) to evaluate experiment data in near real time and trigger events or actions (for example, start or stop cameras or initiate other actions) according to programmed criteria that can be changed for each experiment. The internal trigger would facilitate detailed analysis of the signals that are monitored.

Req. F31 - Digital Acquisition

FCF shall be capable of simultaneously outputting multiple channels of digital signals to PI hardware, as required to accommodate the basis experiments. At lease 16 channels outputting 1-bit at 5 volts shall be provided to experiments that require them.

It is suggested that at least 32 simultaneous TTL-level output channels (1 bit each) at, nominally, zero to 5 volts be provided to control PI hardware.

- ***Req. F32 - Experiment-Specific Capabilities***

  FCF shall be able to accommodate experiment specific computer cards (minimum of two card slots) in an FCF computer near the Fluid Physics work volume and to accommodate PI software for experiment control and analysis (i.e., accommodate PI hardware and software).

The experiment-specific hardware and electronic systems will be used to implement capabilities beyond the scope of the facility design.

- ***Des. DF32***

  It is recommended that an FCF Fluid Physics computer accommodate any or all of the following experiment-specific plug-in boards and associated PI software. The computer should be located near the dedicated Fluid Physics volume. The recommended single board capabilities include:

  DF32.1 State-of-the-art frame grabber
  DF32.2 Oscilloscope board
  DF32.3 Lock-in amplifier
  DF32.4 Time correlator (which support both digital and analog inputs)
  DF32.5 Strain-gauge measurement
  DF32.6 Thermocouple reference and amplifier
  DF32.7 Frequency synthesizer

The desired capabilities should be comparable to the best commercial laboratory equipment available at time of facility design.

- ***Des. DF32.8***

  It is desired that FCF provide a custom electronics enclosure to provide accommodations for high-quality, low-noise measurement capabilities that may require careful protection from electromagnetic interference and temperature variations.

2.4.3 Experiment Control (cont.)

- ***Req. F33 - Image Analysis Capability***

  The FCF shall provide a high performance computing and data-handling capability for onboard image and data processing to enable telescience adaptation of science procedures which actually depend on more data than is feasible to down/up link with the ISS limited bandwidth.

Such a computing facility would enable pattern recognition in images and Fast Fourier Transforms (FFT) of time series data and spatial images. It would allow sorting of data for isolated events of interest or recognize regions of interest within images.

The computer would behave exactly like lab computers used by PI's, where scientists freely uplink their own standard programming language codes and interact with the computer via a real-time terminal using familiar Transmission Control Protocol/Internet Protocol (TCP/IP) functions.

Such a system would be routinely upgraded with evolving computer technology. The I/O bus should be industry standard and high performance. The machine should have 10's of GB of disk space and enough fast RAM such that I/O and computing multitasking are optimized.

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Chapter 3 - Combustion Requirements Envelope

3. COMBUSTION REQUIREMENTS ENVELOPE

3.1 INTRODUCTION

The purpose of this section is to present a description of the combustion science requirements. This is a top-level description which is the intent of this document; more detailed discussions on the requirements are provided in supporting documents such as the individual Science Requirements Documents and hardware capabilities documents. This level of detail is intended to provide "envelope" requirements for necessary capabilities of use to most (if not all) experiments. The "envelopes" are defined in terms of selected detailed requirements from the “basis” (or reference) experiments described in Appendix B.

The experimental method proceeds in the sequence of a logical progression of steps:

- **Hypothesis:** The Principal Investigator proposes an hypothesis and supporting theoretical model of the phenomena to be investigated and defines the experiment(s) to be conducted in order to validate the hypothesis.
- **Definition:** Experiment definition involves establishing the experiment requirements, which include the experiment operating conditions and the experimental measurements to be made.
- **Execution:** The data obtained needs to be managed (i.e., recorded, tagged, and analyzed), and the results are compared with predictions of the theoretical model.

The scope of this section does not include theoretical modeling and data analysis, but focuses on the experimental aspect of the process. Hence, the following material is concerned primarily with experiment operating conditions and experimental measurements.

This section is divided into the following subsections:

- **Experiment Operating Conditions (Section 3.2)**: These are requirements on parameters which define the conditions in which the experiment is conducted.
- **Experiment Measurements (Section 3.3)**: These are requirements on parameters to be measured during the course of the experiment.
- **Data Management (Section 3.4)**: These are requirements on the acquisition and management of data acquired in the course of the experiment.

*Note: Requirement numbers are prefixed with a capital C to indicate that it is a Combustion requirement. Small letter c’s in the requirement pictures (i.e., c1 through c11) indicate the **c**ombustion basis experiment number.*

Facing figure shows a logical evolution of the experimental process which has been used to organize the requirements which follow.

3.2

EXPERIMENT PROCESS MODEL

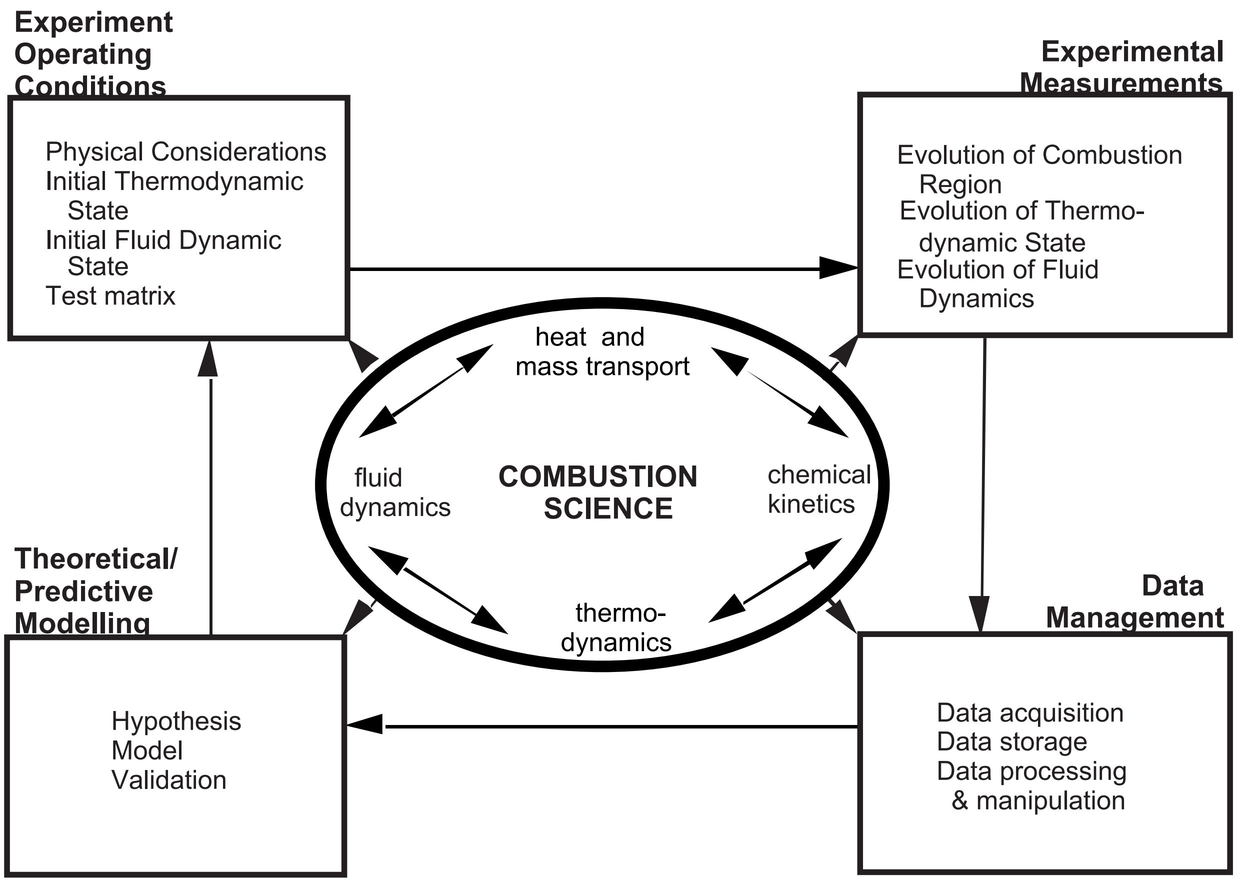


Figure 3-1

EXPERIMENTAL OPERATING CONDITIONS

The requirements discussed in this section pertain to conditions under which experiments are to be conducted. This includes most of the physical bounds necessarily imposed by the FCF as well as the state of the sample prior to initiation of a combustion experiment.

The following parameters are presented below in terms of requirement "envelopes" which are defined in terms of the "basis" (or reference) experiments included in this document.

- **Physical Considerations (3.2.1)**: The FCF must provide the primary capabilities for containment, ignition, and local environment (including residual acceleration) represented by the basis experiments.
- **Initial Thermodynamic State (3.2.2)**: The FCF must accommodate the range of temperatures, pressures, and compositions typical of modern combustion science experiments.
- **Initial Fluid-Dynamics State (3.2.3)**: The FCF must accommodate the range of flow conditions demanded by the basis experiments.
- **Test Matrix (3.2.4)**: The FCF must be scaled to accommodate the large data streams resulting from extended and repetitive experiments.

The following is a list of the requirements on operating conditions listed under the appropriate subsection.

- **3.2.1 - Physical Considerations**:
  - Req. C1 - Test Section Dimensions
  - Req. C2 - Initial Fuel State and Ignition Mechanisms
  - Req. C3 - Acceleration and Vibration
- **3.2.2 - Initial Thermodynamic State**:
  - Req. C4 - Pressure and Temperature
  - Req. C5- Oxidizer Composition
- **3.2.3 - Initial Fluid-Dynamics State**:
  - Req. C6 - Fluid Flow
- **3.2.4 - Test Matrix**:
  - Req. C7 - Number and Duration of Tests

Facing figure illustrates the experimental process previously shown with the Experiment Operating Conditions (this Section 3.2) highlighted. All requirements related to these conditions are in this section.

EXPERIMENT PROCESS MODEL

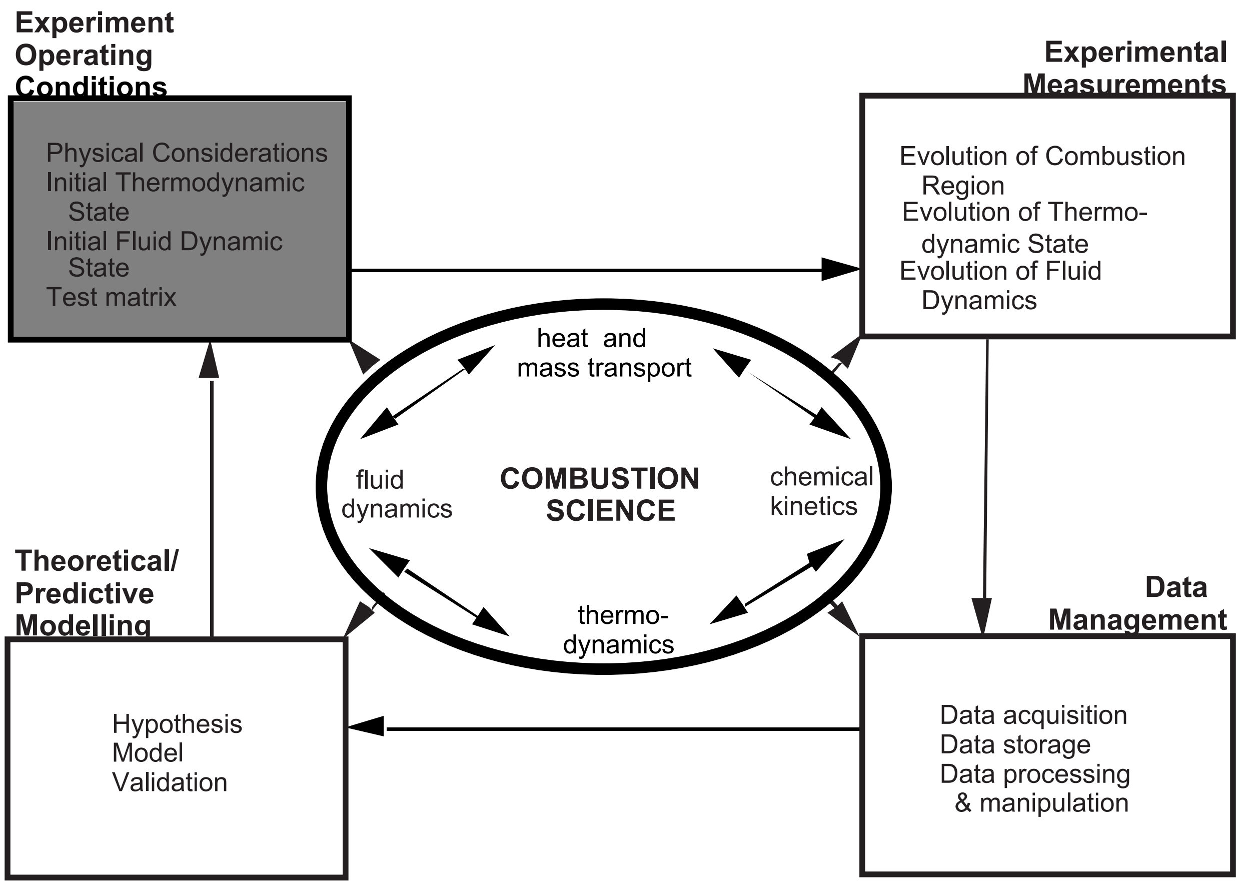


Figure 3-2

3.2.1 Physical Considerations

- ***Req. C1 - Test Section Dimensions***

  The FCF shall provide a combustion chamber with adequate volume and dimensions to accommodate the test sections of basis experiments c1 through c11. Requirements are shown in Figures C1a-b.

The "test section" refers to the physical volume where the combustion phenomena of interest is studied.

The requirements on test section dimensions are provided in terms of volume and the ratio of length (L) to diameter (D) for circular cross-sections (as in basis experiments c1, c2, c5, c6, c7, and c8). For noncircular cross-sections, the three major dimensions (length, width, and height) are provided.

The requirement on test section volume in some instances (e.g., c7) is driven by the need to limit oxygen consumption percentage during the combustion process. It may be acceptable to reduce the volume of the test section if a slow purge and resupply of fresh oxidizer is provided. For experiment c2, the test volume must be refilled with fresh mixture for each test point.

Facing figure shows the distribution of test section volumes and dimensions which define the envelope required to accommodate the basis experiments presented in this document.

Test Section

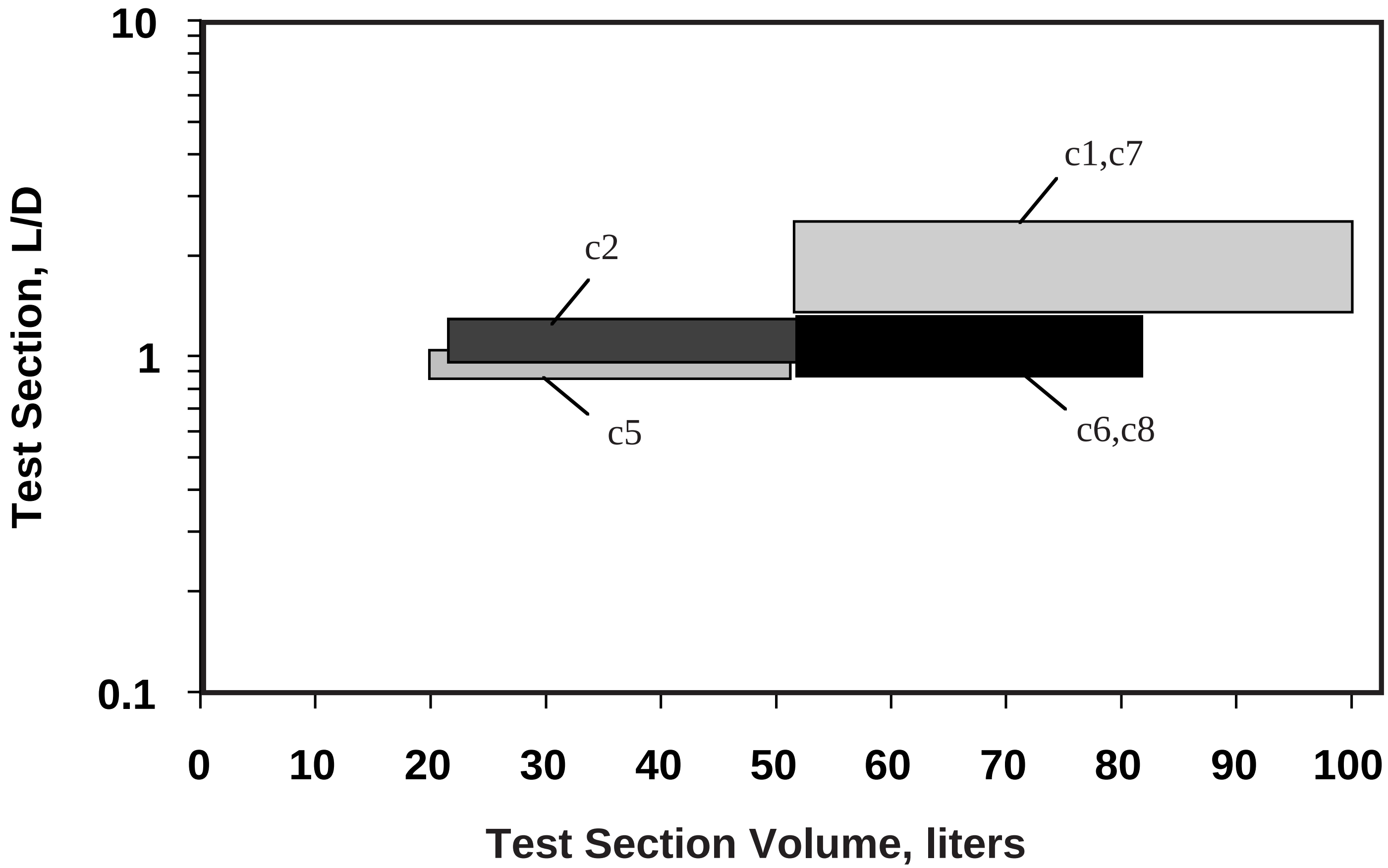


Figure C1a

- ***Req. C1 - Test Section Dimensions (cont.)***

Facing figure shows the distribution of test section dimensions which define the envelope required to accommodate the basis experiments presented in this document.

Test Section Dimensions

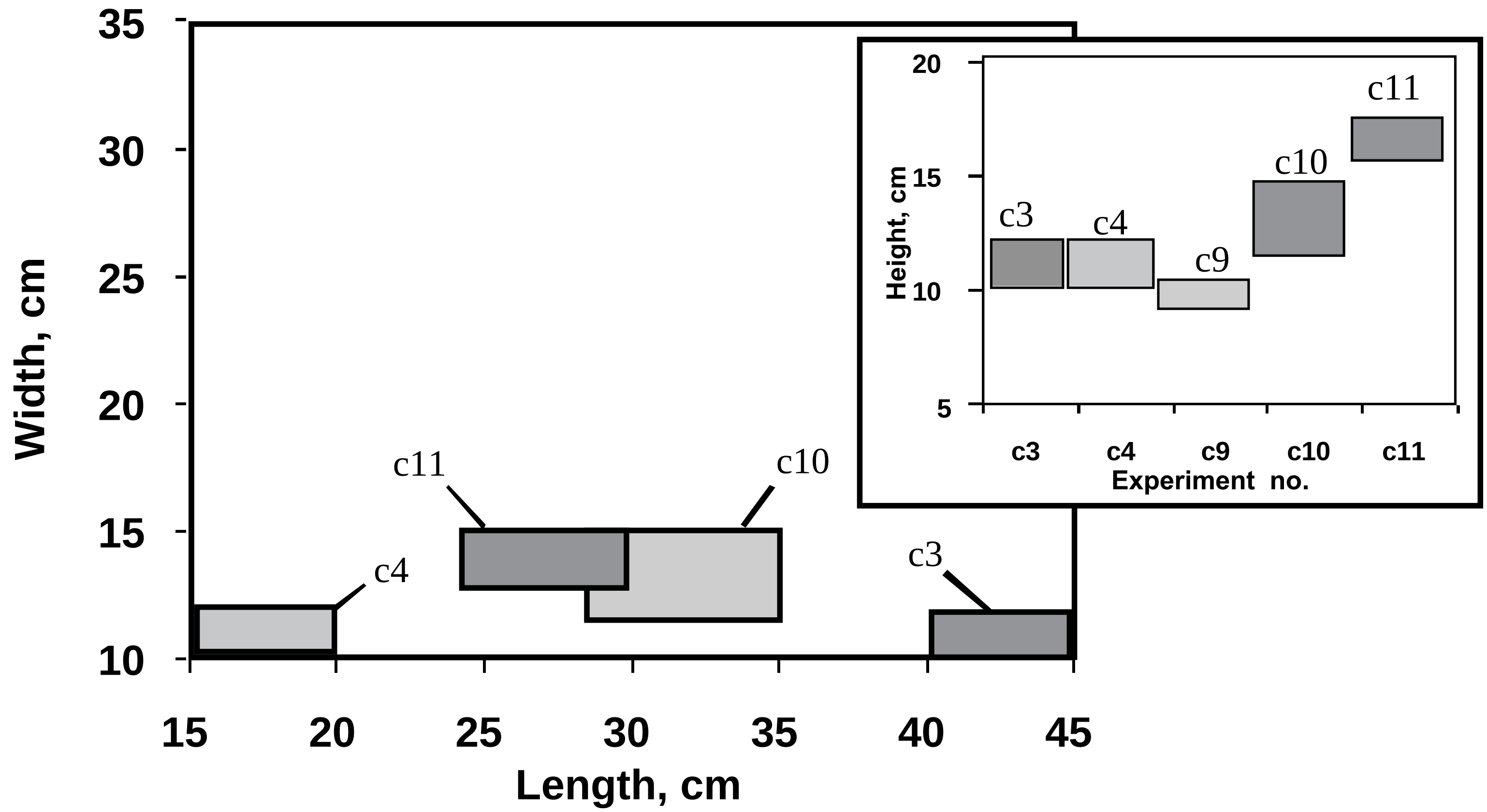


Figure C1b

- ***Req. C2 - Initial Fuel State and Ignition Mechanisms***

  The FCF shall provide a capability for storage, distribution and mixing of fuels and oxidizer. Fuels can be gaseous (e.g., hydrocarbons, alkenes and selected aromatics); liquid (e.g., alcohols and alkanes); or solid fuels (e.g., polymers, wood, cloth, and selected metals).

  The FCF shall also provide power and controls for igniting fuel/oxidizer mixtures using experiment provided igniter mechanisms. Typical ignition mechanisms include hot wires and surfaces, sparks, and lasers.

The initial state of the fuel is important since it largely determines how the fuel is handled. The fuel may initially be in any of the three traditional states of matter: gas, liquid, or solid.

Gas fuel experiments require injectors and/or flame holders. The gaseous fuels called out in the basis experiments include hydrogen, methane, propane, ethylene, acetylene, propylene, and ethane. These may be mixed with diluents such as nitrogen, helium, argon, carbon dioxide, and sulfur hexafluoride.

Liquid fuel experiments require containers, droplet injectors, and deployers. Liquid fuels called out in the basis experiments include toluene, propanol, butanol, n-decane, n-heptane, and methanol. Test mixtures may utilize more than one liquid fuel.

Solid fuel experiments require fuel sample holders. Solid fuels include ashless filter paper, polymethylmethacrylate (PMMA), polyurethane foam (non-flame retardant), wood, cloth, Velcro, cellulose powder, lycopodium powder, polydifluoroethylene (Teflon), polyimide (Kapton), coal, and metals.

The purpose of the igniter mechanism is to initiate the combustion process in a reproducible manner. Ignition mechanisms are herein classified as hot wire, spark, or other. The geometry of the igniter is experiment dependent (e.g., for droplet combustion, the mechanism must maintain symmetry to minimize drop displacement). Ignition mechanisms classified as "other" include hot plates (surfaces) and focused optical sources (such as lasers).

Facing figures show the distribution of sample fuel types and ignition methods within the basis experiments presented in this document.

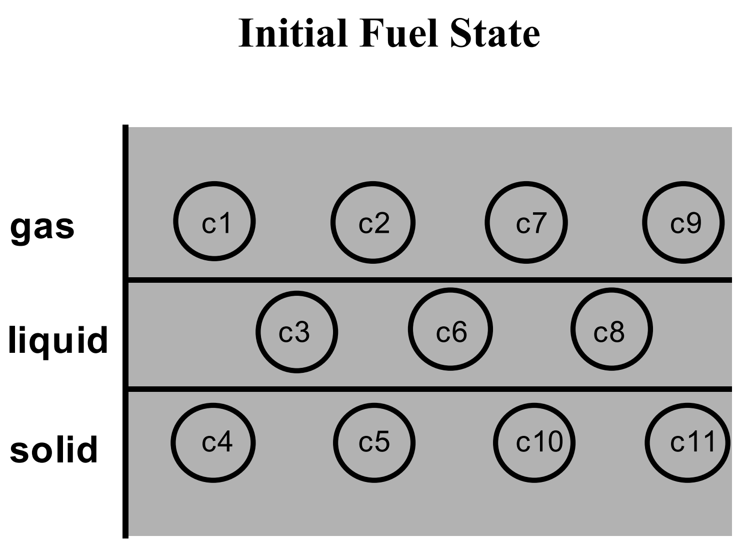


Figure C2a

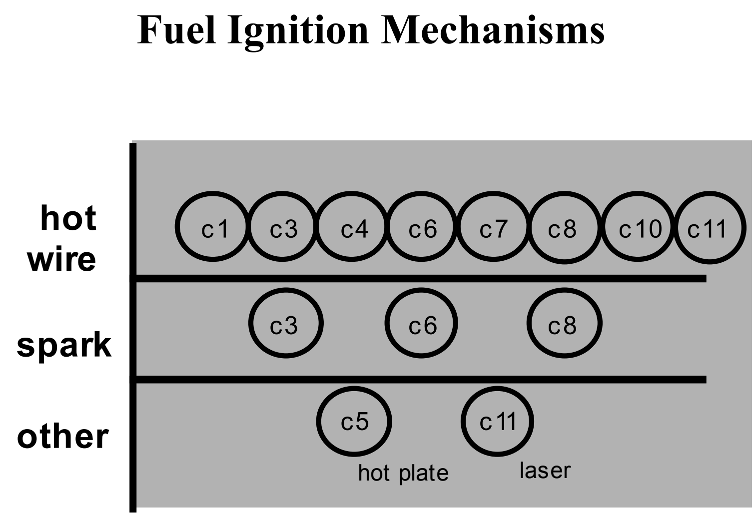


Figure C2b

- ***Req. C3 - Acceleration and Vibration***

  The FCF shall provide an environment which minimizes the "quasi-steady state" accelerations, vibratory disturbances, and transient impulses. Requirements are shown in Figure C3.

The low-gravity (near "microgravity") environment of an orbiting laboratory provides the primary rationale for doing experiments in space. The "pure" environment of a simple, free-falling orbiting body can be disturbed (indeed, degraded) by three factors:

- quasi-steady accelerations exhibiting persistent direction or very low frequency (i.e., pseudo-dc) modulation due to off-sets from the center of gravity, vehicle drag characteristics, asymmetric orbits, etc.
- vibratory motions of structure and dynamics of a large, manned vehicle such as International Space Station, and
- impulse motions such as collisions during orbiter docking or impacts of hatches or doors, etc.

The acceleration environment in which experiments are conducted is extremely important in interpreting results. The requirements called out by the basis experiments are shown below in terms of normalized acceleration level as a function of frequency. The low frequency limits (nominally less than 1 Hz for this analysis) are of the order of the inverse of the burn time and may be construed as the quasi-steady acceleration levels required to assure "microgravity" behavior for the combustion phenomena of interest in the pertinent basis experiment.

It should be noted that effects of "g-jitter" (vibratory or unsteady acceleration levels) on combustion phenomena are not fully understood. The acceleration requirements for most experiments, exhibited below, were obtained by utilizing the quasi-steady level identified for each experiment and assuming a $1/\omega$ (ω is frequency) dependence of g-jitter induced velocity when flows are small. Thus, denoting the quasi-steady g-level as g_s, g-jitter requirements may be stated as follows:

$$\text{For } \omega < \omega_0, \quad g' < \alpha g_s$$
$$\text{For } \omega > \omega_0, \quad g' < (\omega - \omega_0)\, \alpha g_s + \alpha g_s$$

Here, ω_0 is a small value of ω where quasi-steady conditions are approximately satisfied and α is a number close to unity. For basis experiment c2, the acceleration requirements are:

$$\text{For } \omega < 2\text{Hz}, \quad g' \leq 1 \quad 4 \times 10^{-4} g_0$$
$$\text{For } \omega > 2\text{Hz}, \quad g' \leq 10^{-4} \times \omega^2 g_0$$

Where g_0 is the standard value of normal gravity acceleration.

- ***Des. DC3.1***

  It is desirable to have a quasi-steady acceleration level of $10^{-6} g_0$ during conduct of the experiments.

Facing figure shows the distribution of the upper bounds for quasi-static and vibratory excitation called out for selected basis experiments. It should be noted that these all reside within the bounds called out in SSP 41000D.

Acceleration Requirements

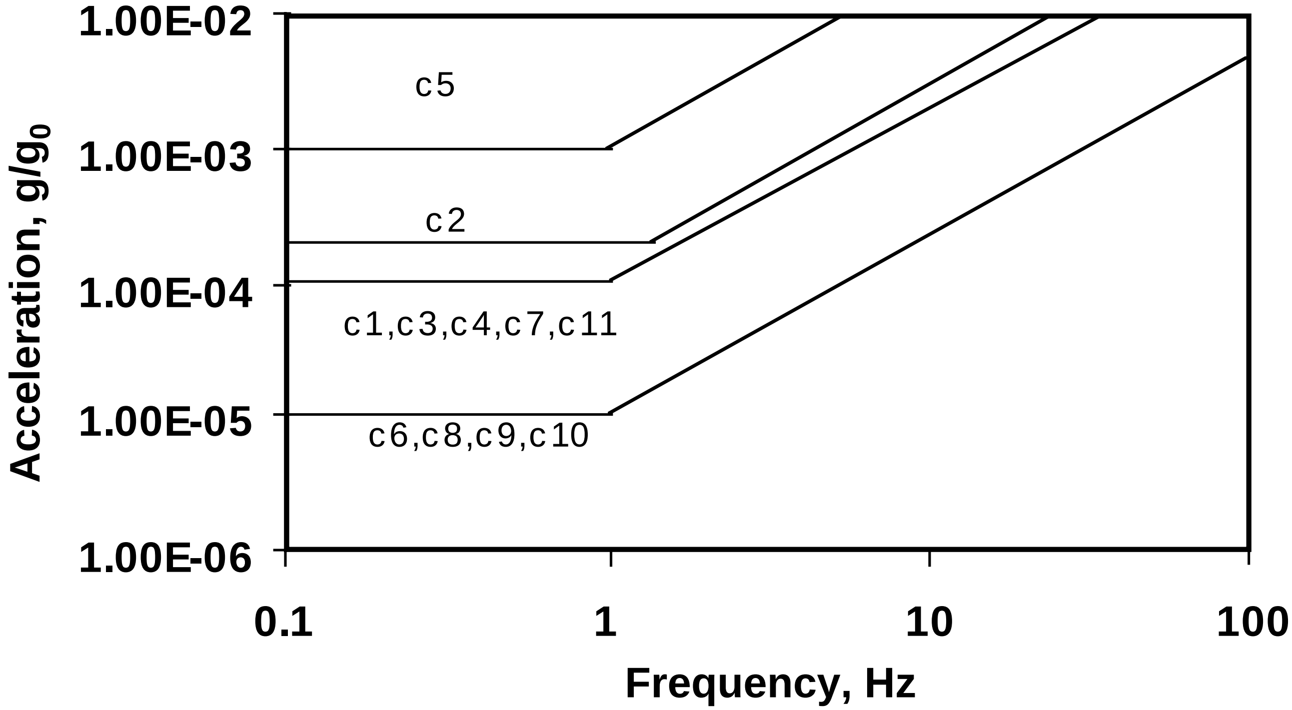


Figure C3

3.1.2 Initial Thermodynamic State

- ***Req. C4 - Pressure and Temperature***

  The FCF shall provide pressure containment and control for initial gas pressures in the range of 0.02 to 3 atmosphere. The FCF shall provide containment and control for the pressure to remain constant within 5% throughout the test time. It shall provide containment for pressure increases to 9 atmosphere (absolute). The FCF shall provide control for initial gas temperatures of 268 to 320 K. Condensed phase fuel temperatures shall be controllable to ±1 K in the range 268 to 315 K at the start of testing.

The initial conditions of pressure and temperature, in conjunction with chemical composition, determine the initial thermodynamic state. Requirements on initial test section pressure and temperature identified in the basis experiments are shown below. The oxidizer temperature range is to be considered representative of the gas-phase temperature (e.g., in basis experiment c2, the gas phase is a mixture of both oxidizer and fuel components).

For most experiments using a condensed phase fuel (solid or liquid), the oxidizer and fuel temperatures are nominally the same. For experiment c3, the restrictions on allowable temperatures depend upon the fuel and these determine the combustion regime (i.e., pulsating versus steady flame spread). Thus, for this experiment, the fuel and oxidizer temperature may need to be controlled depending upon the Space Station ambient conditions.

The range in initial oxidizer and fuel temperature for the other experiments reflects the tolerance on variation from standard temperature conditions allowable.

In some instances (not included in these basis experiments), pressure requirements may range in excess of 100 atm. These experiments will require considerably smaller volumes than in current concepts for the Test Section (on the order of 8 liters).

It is also to be noted that as a result of the combustion process, the pressure can exceed the initial value during or at the conclusion of the test.

Temperature control of test section components, including the walls and burner assembly, may be required in some experiments. The cooling rate will not, in general, exceed the heat release rate from the combustion phenomena. These rates range from a few watts for weak flames to approximately 2 kW for more vigorous flames.

Facing figure shows the distribution of initial temperatures and pressures which define the envelope required to accommodate the basis experiments presented in this document.

Operating Conditions in Pressure and Temperature

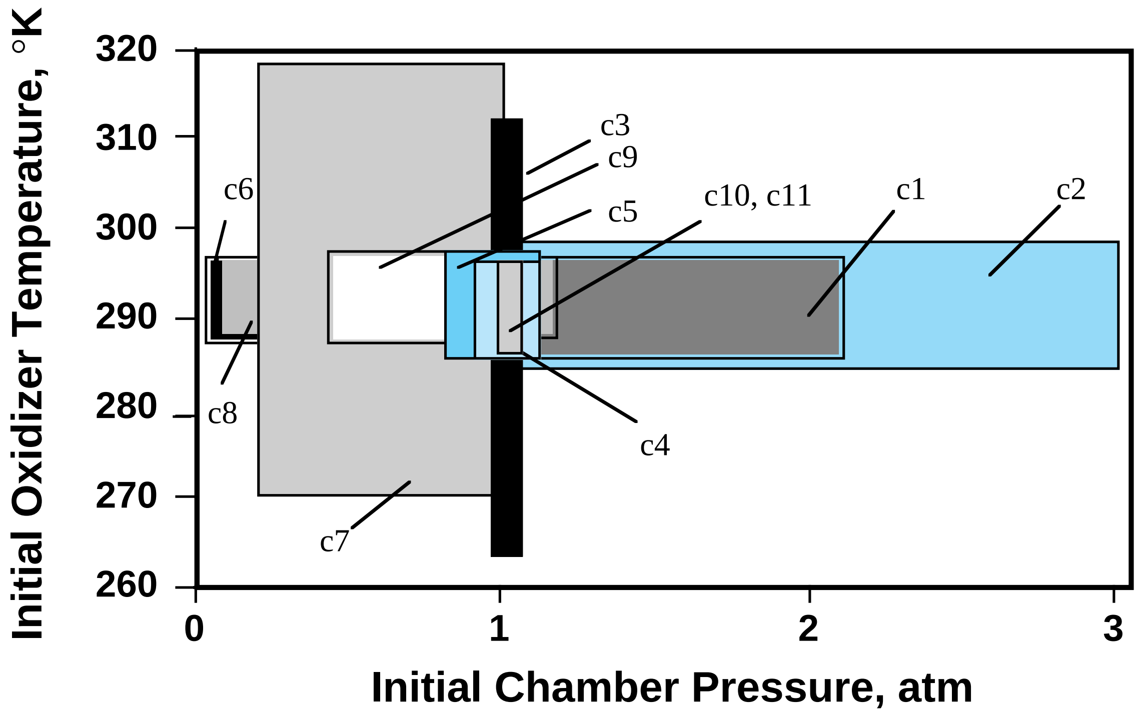


Figure C4a

- ***Req. C4 - Pressure and Temperature (cont.)***

Facing figures show the distribution of initial temperatures which define the envelope required to accommodate the basis experiments presented in this document.

Operating Conditions in Fuel and Oxidizer Temperature

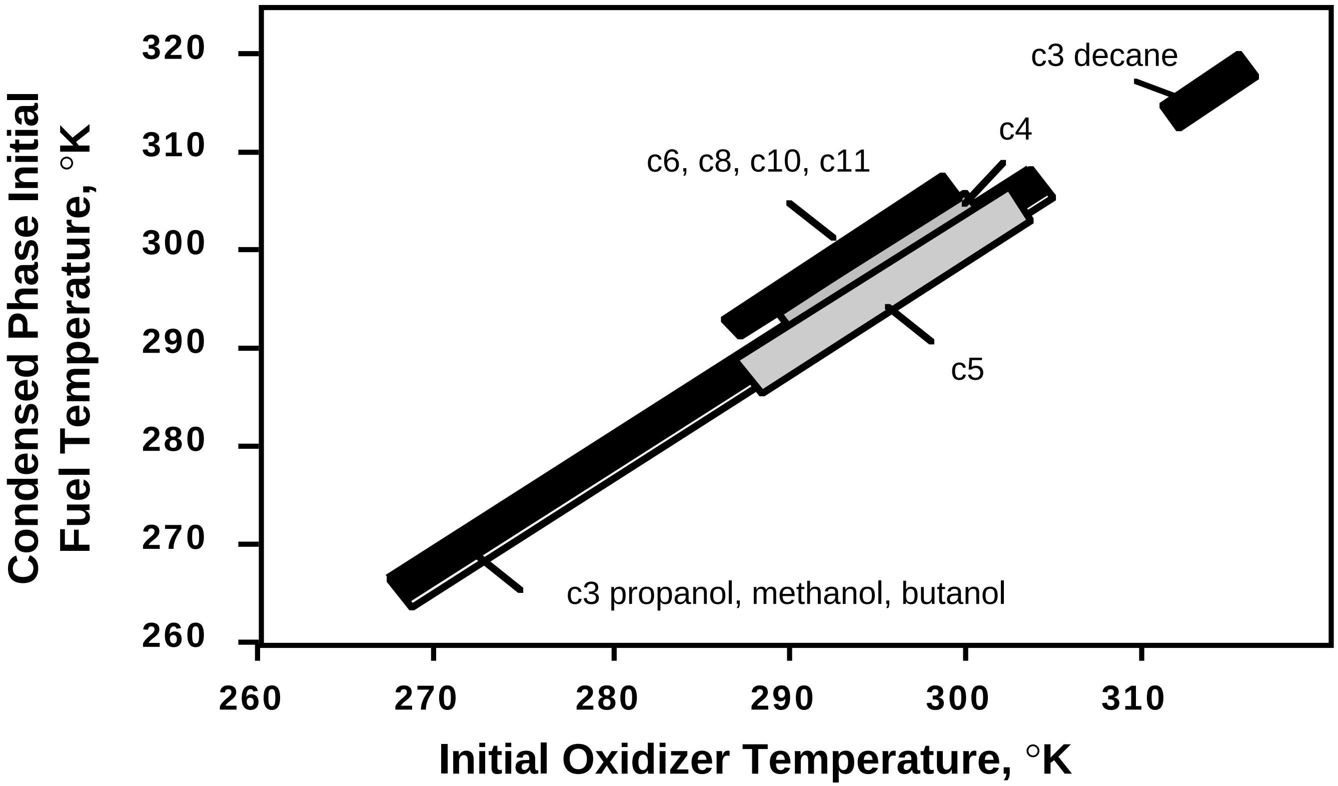


Figure C4b

- ***Req. C5 - Oxidizer Composition***

  The FCF shall provide oxidizer, which will generally be a mixture of oxygen and one or more diluents. Oxygen concentration in this mixture will vary over the range of 0 to 70%. Selected requirements are shown in Figures C5a-b.

  The FCF shall also have the capability to dispense pre-mixed oxidizer/fuel mixtures from gas bottles into the combustion chamber.

The combustion characteristics are strongly dependent upon the oxygen concentration, as well as the nature and amount of diluents. The concentration ranges shown below are expressed in terms of volume percent of diluent and oxygen. The sum of the respective volumes must be 100% (several bars plotted below are offset for clarity). For premixed flames, the fuel is also mixed with the oxidizer and these systems are not reflected in the graph. The FCF must provide a capability for delivering the contents of bottles containing fuel/oxidizer mixtures to the combustion chamber. It is, however, desirable to have the ability to deliver flow from two premixed bottles into the chamber.

Diluents may include N_2, CO_2, Ar, He, SF_6, Xe, and other noble gases.

- ***Des. DC5.1***

  It is desirable to have the ability to burn in a 100% oxygen environment.

- ***Des. DC5.2***

  It is desirable to have the ability to supply gas from more than one premixed bottle for a single test run.

Facing figure shows the distribution of oxidizer and diluent concentrations which define the envelope required to accommodate the basis experiments (non-premixed cases) presented in this document. Note that for visual clarity, the requirements for the different experiments are offset from each other.

Oxidizer Composition

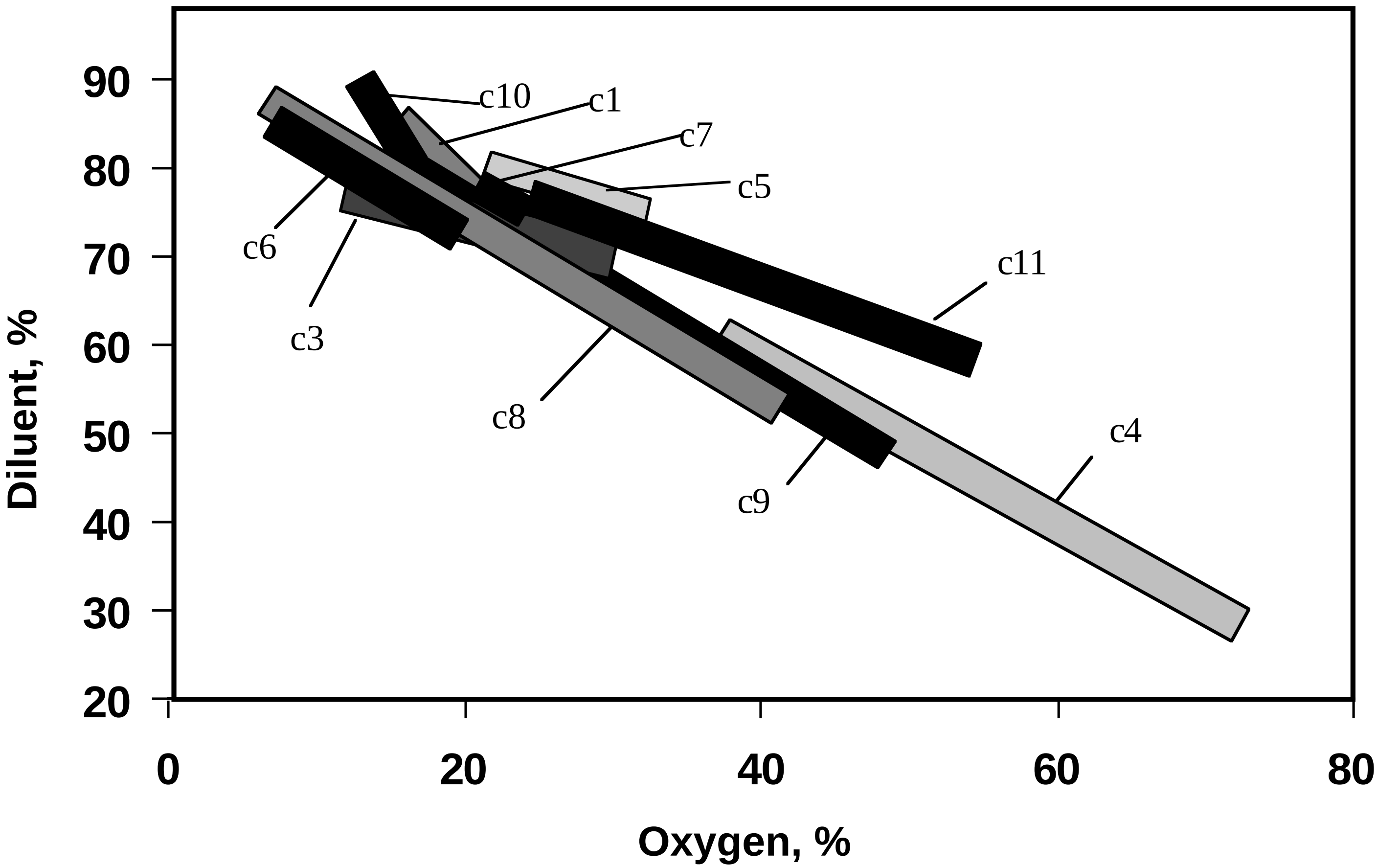


Figure C5a

- ***Req. C5 - Oxidizer Composition (cont.)***

Facing figure shows the distribution of precision and accuracy for oxidizer and diluent concentrations which define the envelope required to accommodate the basis experiments (non-premixed cases) presented in this document

Oxidizer Preparation and Measurement Accuracy

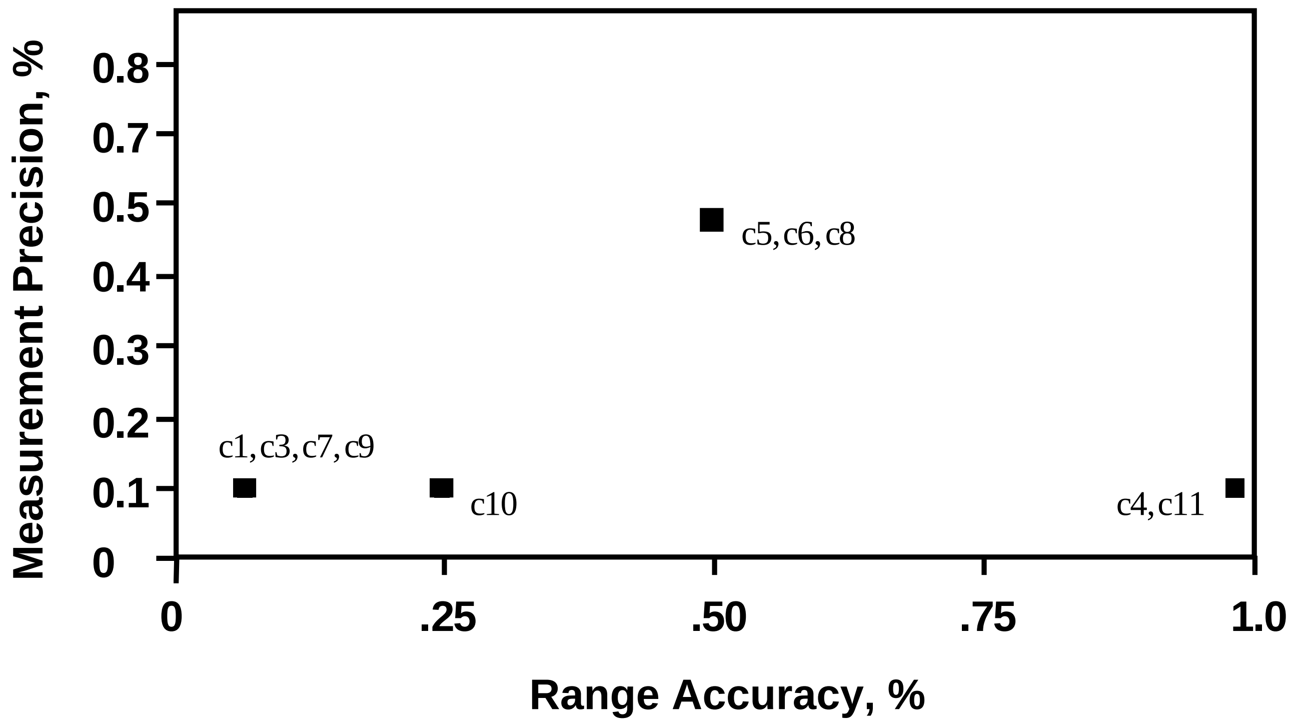


Figure C5b

3.1.3 Initial Fluid Dynamics State

- ***Req. C6 - Fluid Flow***

  The FCF shall provide controlled flow of fuel over the volume flow rate range of 0 to 30 cc/sec under standard conditions (i.e., scc/sec) and controlled flow of oxidizer over the volume flow rate range of 0 to 4,000 scc/sec with an accuracy of 10% and a stability of 5% of the set point.

This requirement deals with the initial flow of gases through the experiment test section. The graph below displays these initial flow rates for both oxidizer and fuel flows.

In some experiments, the fuel may be flowing and the oxidizer is initially stationary, and vice-versa. In general, flowing fuel would be in the gaseous state; however, in some instances, condensed phase fuel samples may be translated relative to the oxidizer.

In some cases, e.g., c3, it may be acceptable to utilize a recirculating flow; however, the flow-through capability must be maximized to the extent possible.

The graph does not contain information on the flow of premixed fuel and oxidizer (no basis experiment requires such conditions).

- ***Des. DC6.1***

  It is extremely desirable to have the capability to flow premixed fuel and oxidizer through the test section or PI-hardware in a controlled manner. Such experiments cannot utilize a recirculating flow. Overall (fuel and oxidizer) flow rates may range to 4,000 scc/sec.

Facing figure shows the distribution of oxidizer and fuel flow rates which define the envelope required to accommodate the basis experiments presented in this document.

Fuel and Oxidizer Flow Rates

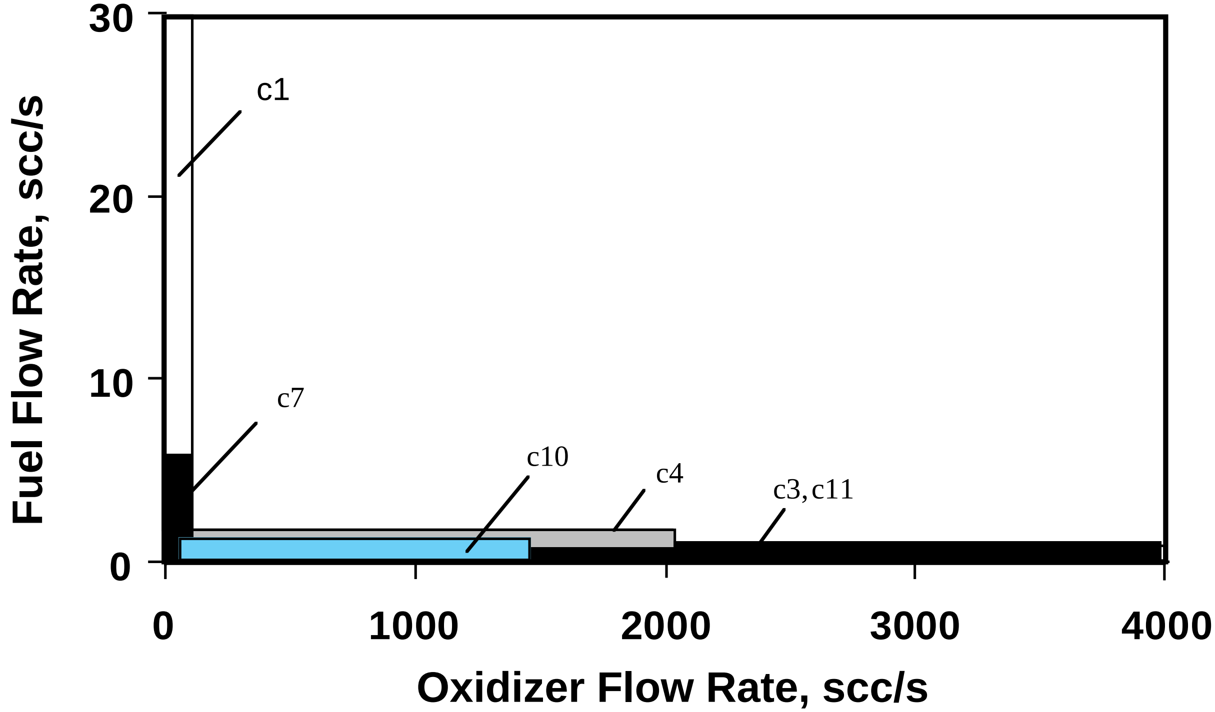


Figure C6

3.1.4 Test Matrix

- ***Req. C7 - Number and Duration of Tests***

  The FCF shall provide all necessary support (e.g., data storage, fuel, oxidizer, and diluent storage and distribution, combustion product collection and disposal) to accomplish experiments having ranges of duration and repetition represented by the basis experiments described in this document. Requirements are shown in Figure C7.

The number of tests displayed on the graph below is an estimate of the number of different, successful test points required to validate the hypotheses of the experiment and obtain definitive data.

The time per test includes time for preburn operations associated with the test point. Examples of these operations include liquid fuel deployment in the experiment container (e.g., for c3) and droplet deployment and stretching (e.g., for c6 and c8). Many of these pre-burn operations require the reduced-gravity environment.

Facing figure shows the distribution of test times and number of tests which define the envelope required to accommodate the basis experiments presented in this document.

Estimates of Number of Tests and Test Times

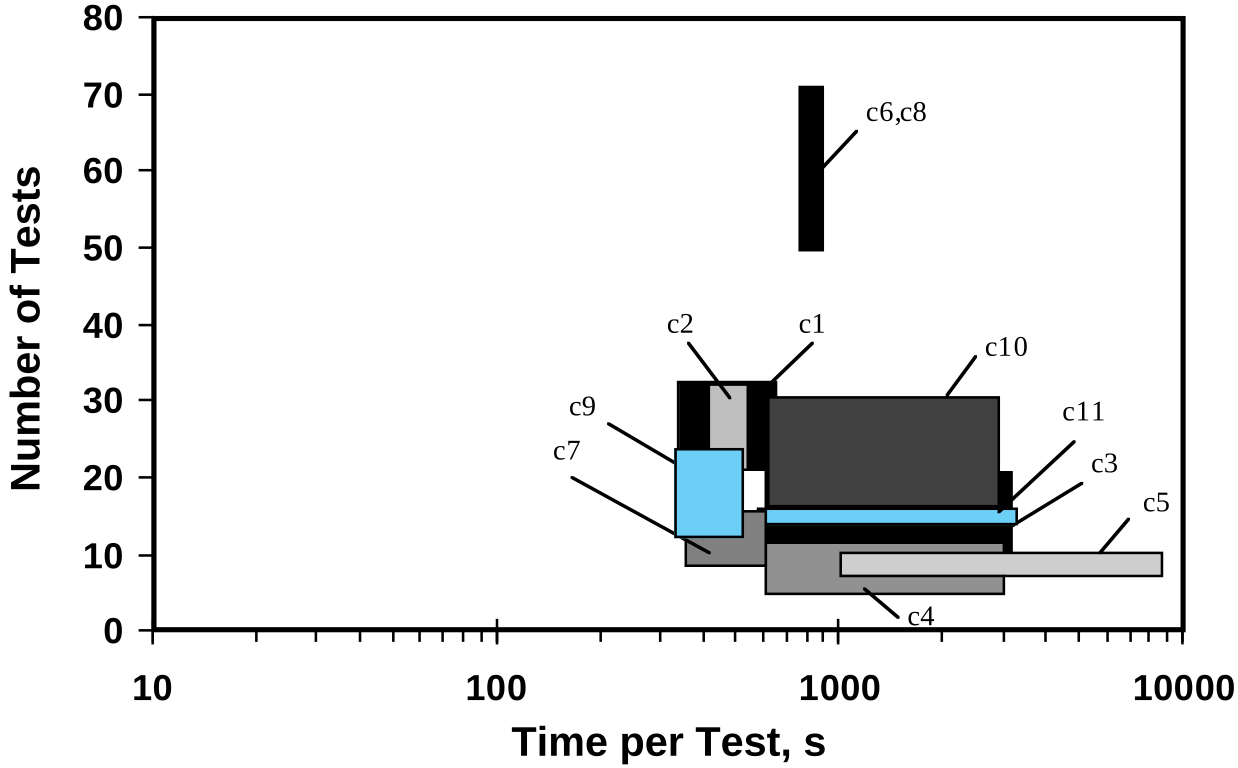


Figure C7

3.3 EXPERIMENTAL MEASUREMENTS

The requirements discussed in this section pertain to measurements that must be performed in the course of most combustion experiments.

The following parameters are presented below in terms of requirement "envelopes" which are defined in terms of the basis experiments included in this document:

- **Evolution of the Combustion Region (3.3.1)**: The FCF provides power, control and data acquisition capabilities for imaging and optical measurement.
- **Evolution of the Thermodynamic State (3.3.2)**: The FCF provides power, control and data acquisition capabilities for measurement of the range of temperatures, pressures, and compositions occurring in the combustion process.
- **Evolution of the Fluid-Dynamics (3.3.3):** The FCF provides power, control and data acquisition capabilities for measurement of dynamic flow and acceleration environments during experiment operation.

The following is a list of the requirements on experimental measurements listed under the appropriate subsection. Suggestions on diagnostic techniques are also indicated.

- **3.3.1 - Evolution of the Combustion Region:**
  - Req. C8 - Visible Imaging
  - Req. C9 - IR Imaging
  - Req. C10 - UV Imaging
- **3.3.2 - Evolution of the Thermodynamic State**:
  - Req. C11 - Temperature Point Measurements
  - Req. C12 - Temperature Field Measurements
  - Req. C13 - Pressure Measurements
  - Req. C14 - Chemical Composition and Soot Measurements
  - Req. C15 - Radiometry
- **3.3.3 - Evolution of the Fluid-Dynamics**
  - Req. C16 - Velocity Point Measurements
  - Req. C17 - Full Field Velocity Imaging
  - Req. C18 - Acceleration Measurements

Facing figure illustrates the experimental process previously shown with the Experimental Measurements (this Section 3.3) highlighted. All requirements related to these measurements are in this section.

EXPERIMENT PROCESS MODEL

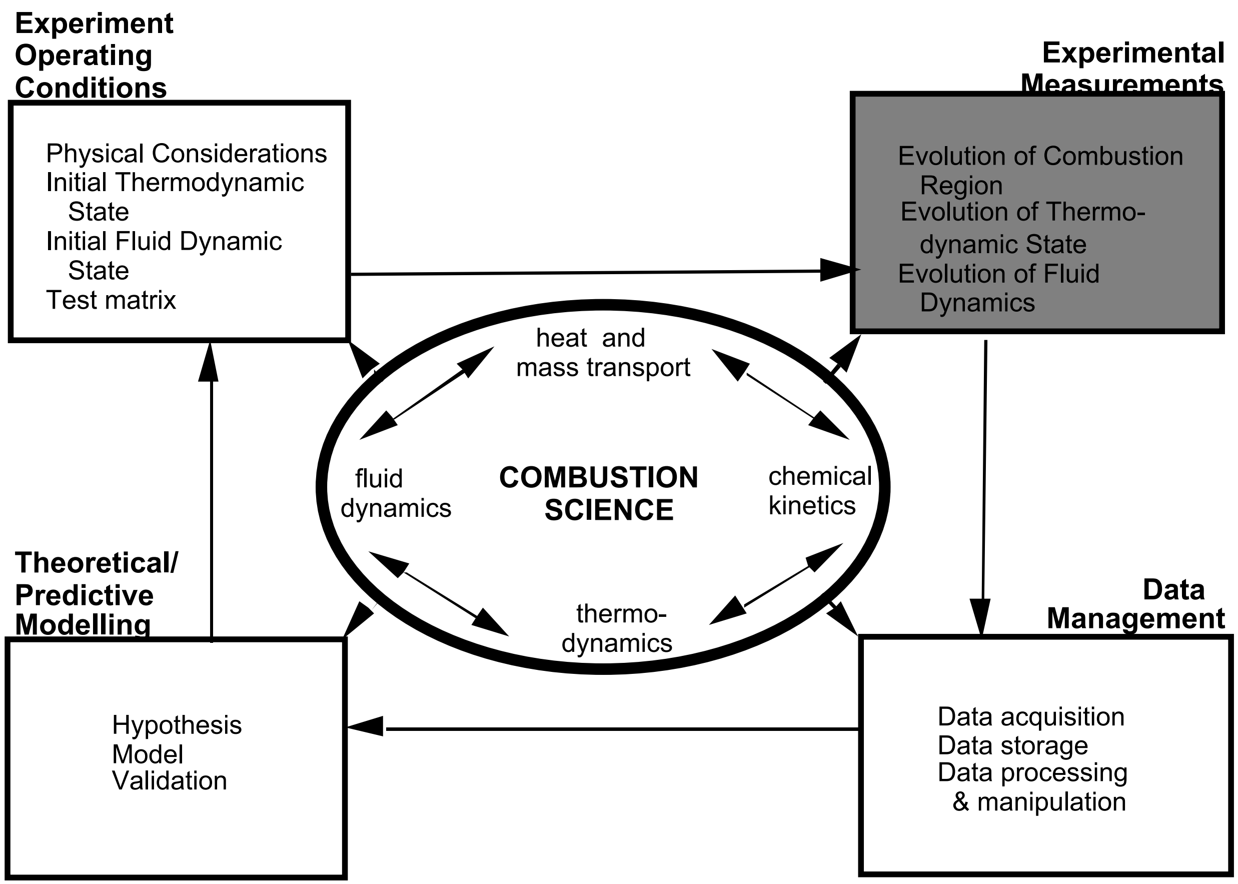


Figure 3-3

3.3.1 Evolution of the Combustion Region

- ***Req. C8 - Visible Imaging***

  The FCF shall provide imaging systems, illumination sources, power, control and data acquisition capabilities for imaging in the visible spectrum (400-700 nm). The imaging systems shall accommodate the envelopes of parameters defined for the basis experiments. Framing rates to 100/sec are required. Requirements are shown in Figure C8a-c. When the visible sensor is used primarily as a temperature, velocity, or soot measurement sensor, additional requirements apply (see Requirements C12, Temperature Field Measurements, C14, Chemical Composition and Soot Measurements, and C17, Full Field Velocity Imaging).

Images of the combustion region in the visible spectrum provide information on flame shape and flame spread. For droplet combustion studies, the images also serve to track the droplet diameter as a function of time.

Important parameters associated with these images are field of view, depth of field, spatial resolution, and framing rate. The ranges of these parameters required for the basis experiments are displayed in the following graphs and serve to define "envelopes." The "axial" direction refers to the direction of flame propagation or fuel flow.

Color imaging is required for most of the basis experiments. Orthogonal or near-orthogonal views are required for some cases to verify the symmetric nature of the flame, or to obtain different views of the combustion phenomena.

Back lighting is required for the droplet combustion experiments to enable tracking of droplet diameter. The imaging system must account for droplet drift perpendicular to the imaging plane.

- ***Des. DC8.1***

  It is desirable to accommodate framing rates to 1,000/sec for visible imaging.

Suggested Techniques: High resolution, low light sensitive, color, and black and white video cameras. These may require band pass filtering with RGB filters and subsequent recombination to obtain color composite images.

Facing figure shows the distribution and range of parameters for resolution, and frame rate for visible imaging which define the envelope required to accommodate the basis experiments presented in this document. Additional figures are on the following pages.

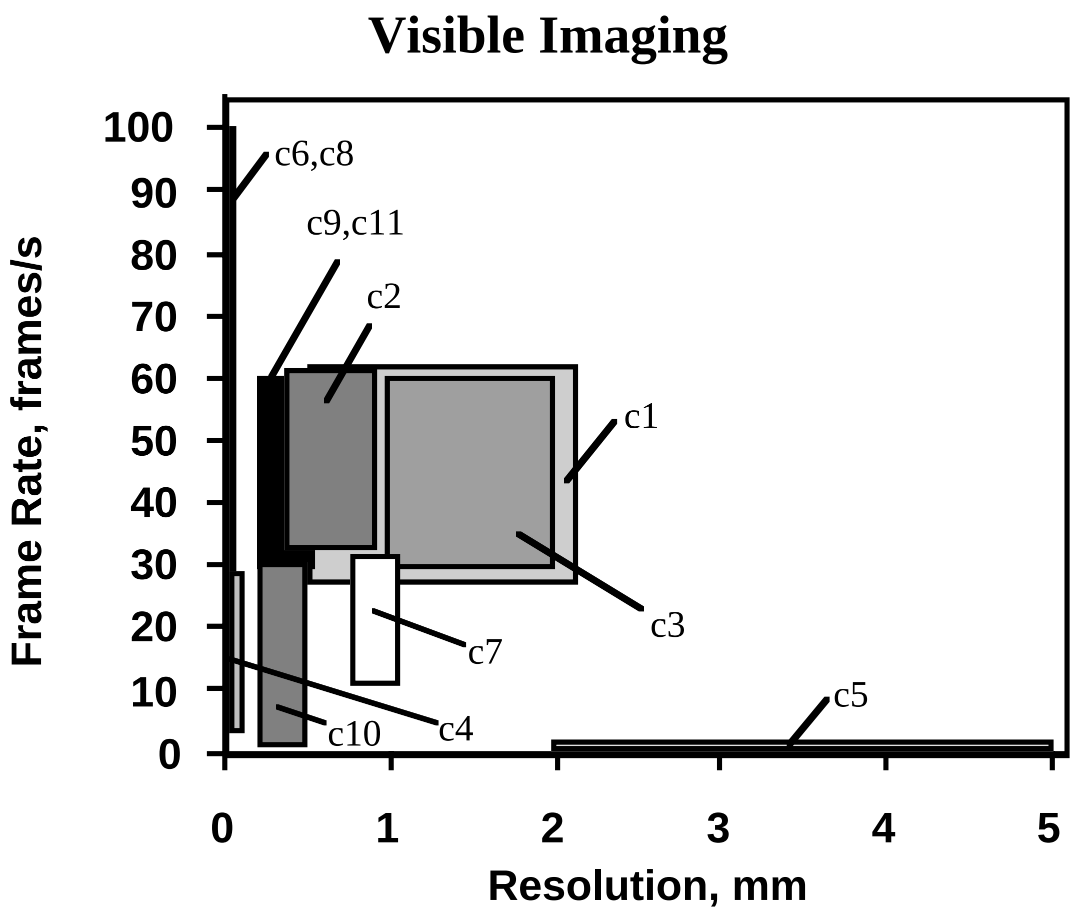

Visible Imaging
Frame Rate, frames/s
100
90
80
70
60
50
40
30
20
10
0
c6,c8
c9,c11
c2
c1
c3
c7
c4
c10
c5
0
1
2
3
4
5
Resolution, mm

Figure C8a

- ***Req. C8 - Visible Imaging (cont.)***

Facing figure shows the distribution and range of parameters for field of view and depth of field for visible imaging which define the envelope required to accommodate the basis experiments presented in this document. An additional figure is on the following pages.

Visible Imaging

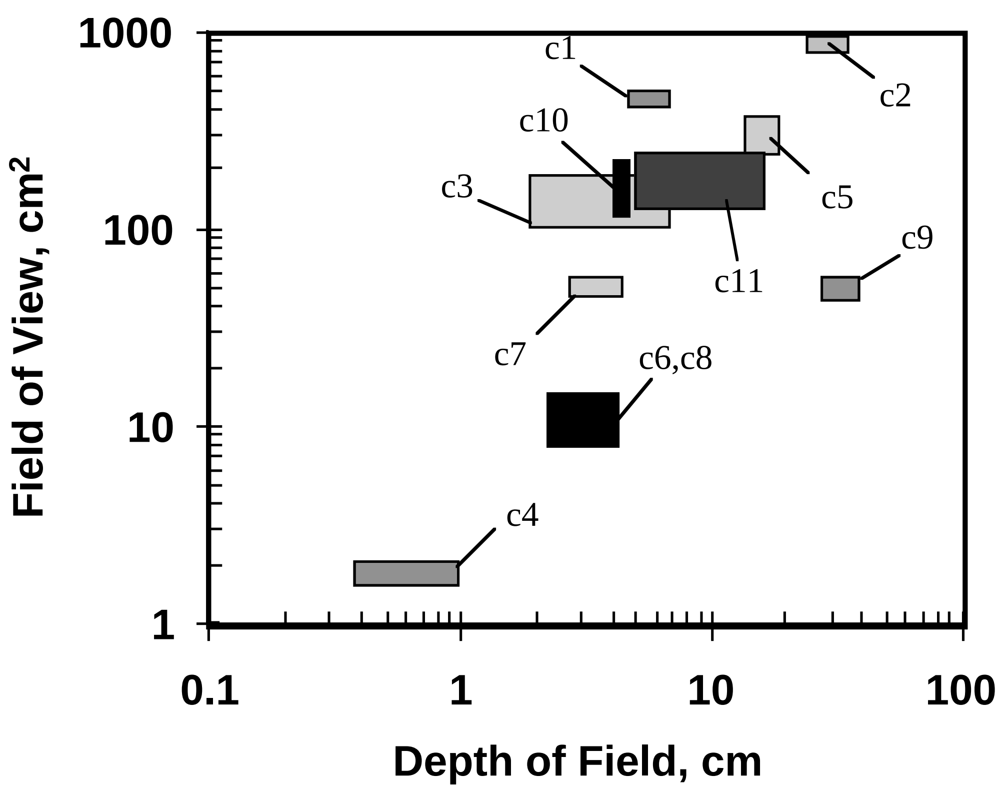
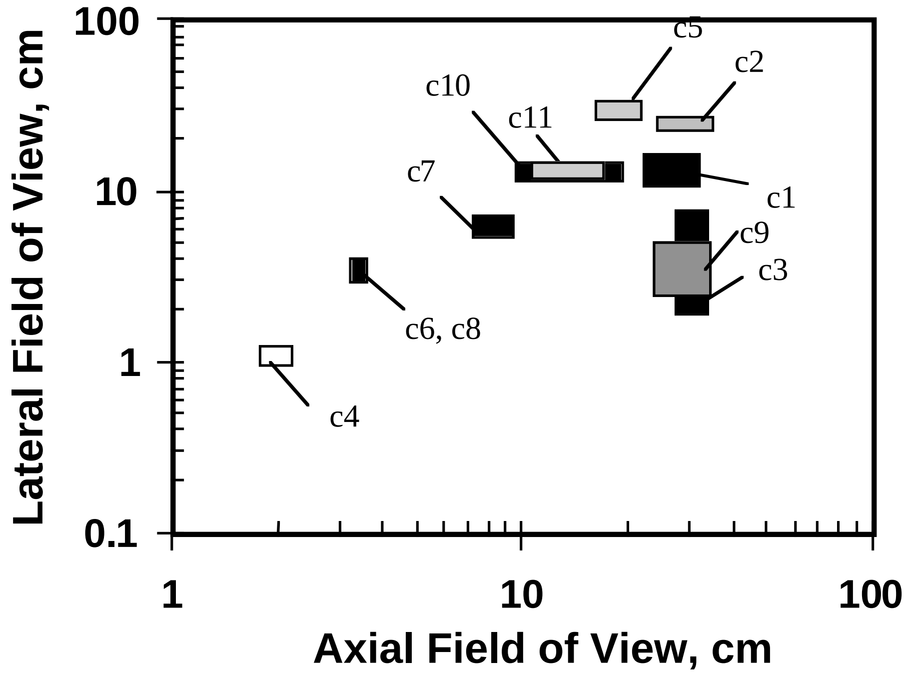


Figure C8b

- ***Req. C8 - Visible Imaging (cont.)***

Facing figure shows the distribution and range of parameters of lateral and axial field of view for visible imaging which define the envelope required to accommodate the basis experiments presented in this document.

Visible Imaging



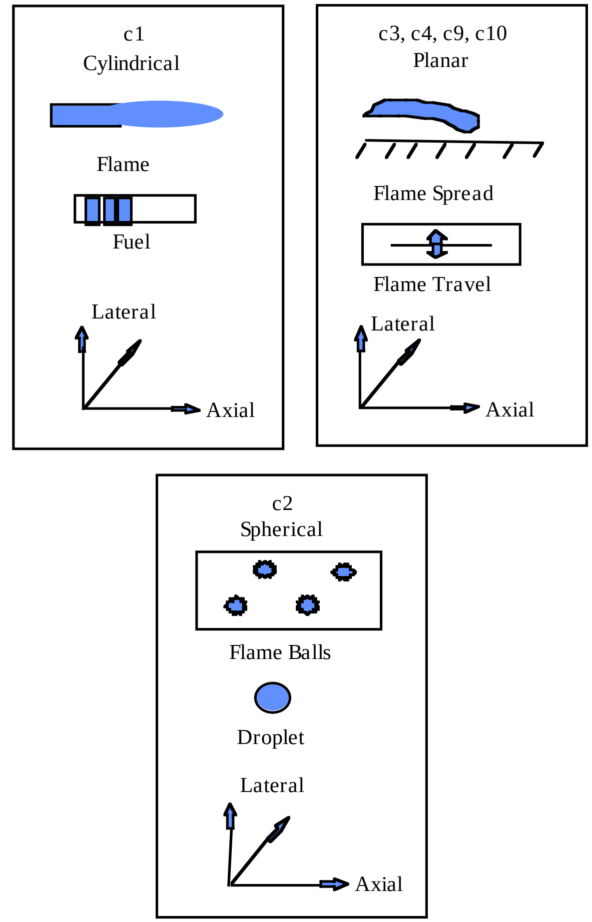


Figure C8c

- ***Req. C9 - IR Imaging***

  The FCF shall provide imaging systems, power, control and data acquisition capabilities to image flames and surfaces in the infrared spectrum in the wavelength range of 1,000 to 5,000 nm and 8,000 to 14,000 nm. Framing rates to 60/sec are required. Requirements are shown in Figures C9a-c. When the infrared imager is used primarily as a temperature sensor, additional requirements apply (see Requirements C11 and C12, Temperature Measurements).

Images of the combustion region at wavelengths in the infrared spectrum provide information about the spatial distribution of combustion species concentration and temperature. Two wavelength ranges are of primary interest: 1,000 to 5,000 nm and 8,000 to 14,000 nm. When the surface of condensed phases are viewed, the surface temperature can be inferred from knowledge of the surface emittance.

Important parameters associated with these images are field of view, depth of field, spatial resolution, and framing rate. The ranges of these parameters required for the basis experiments are displayed in the following graphs and serve to define "envelopes." The "axial" direction refers, again, to the direction of flame propagation or fuel flow.

When the infrared imager is used primarily as a temperature sensor, additional requirements apply (see Requirements C11 and C12, Temperature Measurements).

- ***Des. DC9.1***

  It is desirable to accommodate framing rates to 1,000/sec for IR imaging.

Suggested Techniques: High resolution infrared cameras with imaging wavelengths in the 1,000 to 5,000 nm and 8,000 to 14,000 nm ranges.

Facing figure shows the distribution and range of parameters for resolution and frame rate for infrared imaging which define the envelopes required to accommodate the basis experiments presented in this document. Additional figures are on the following pages.

Infrared Imaging

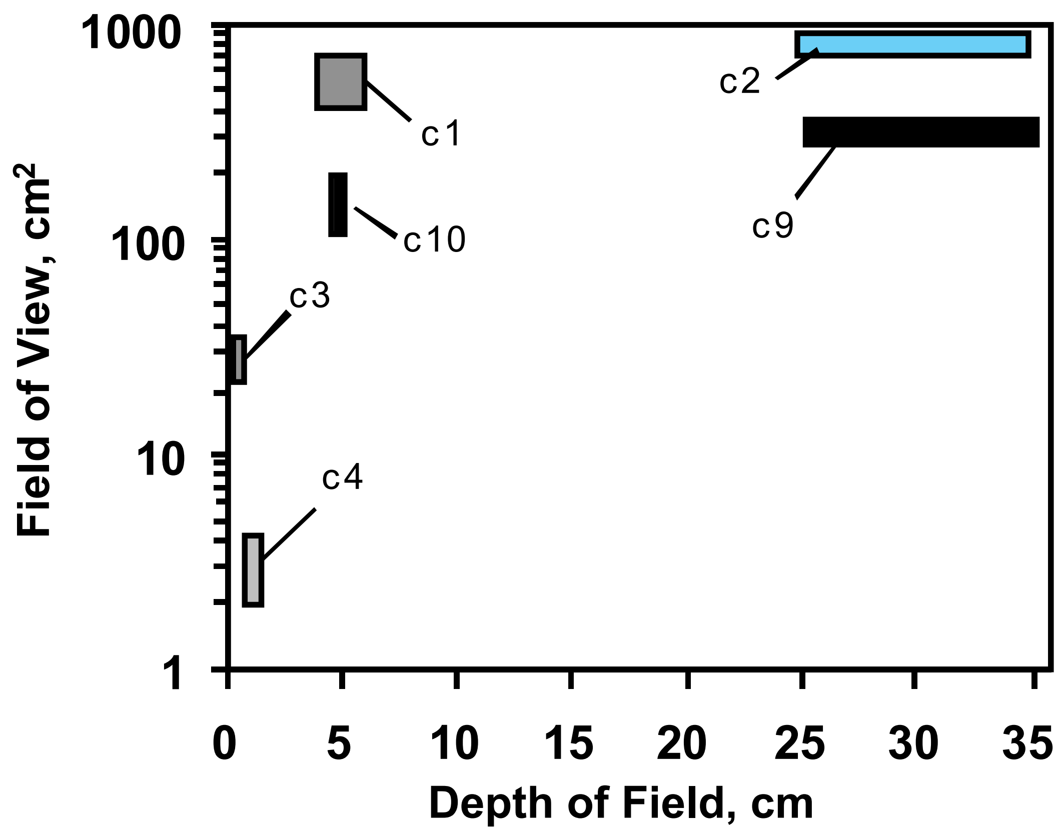


Figure C9b

- ***Req. C9 - IR Imaging (cont.)***

Facing figure shows the distribution and range of parameters for field of view, and depth of field for infrared imaging which define the envelopes required to accommodate the basis experiments presented in this document. An additional figure is on the following page.

Infrared Imaging

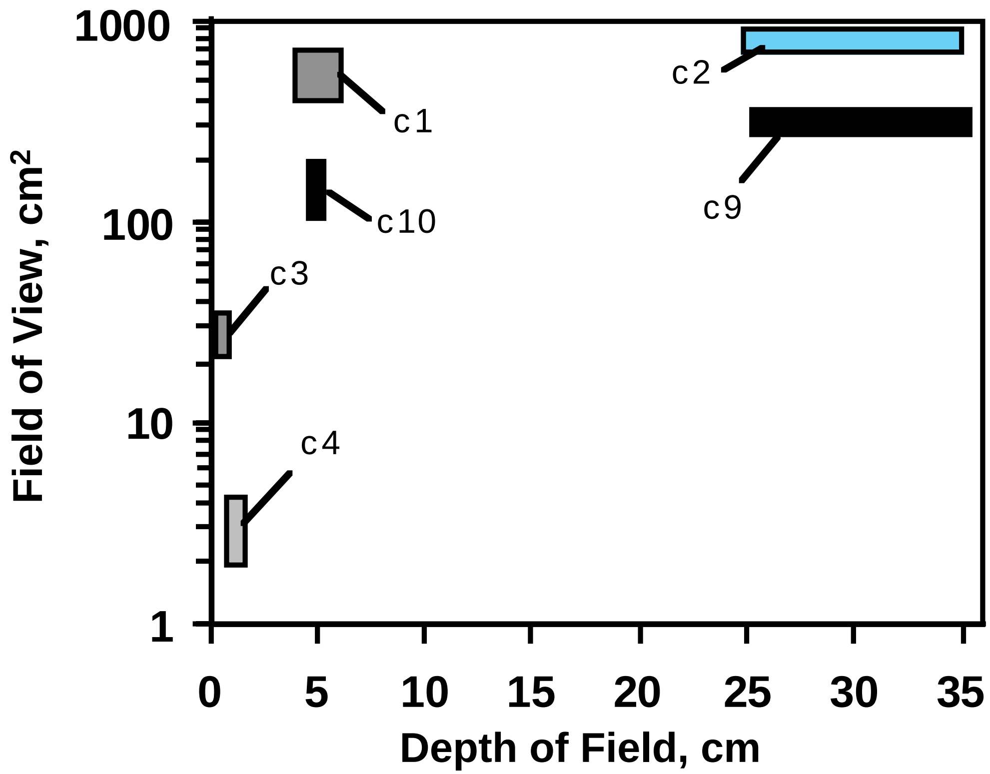
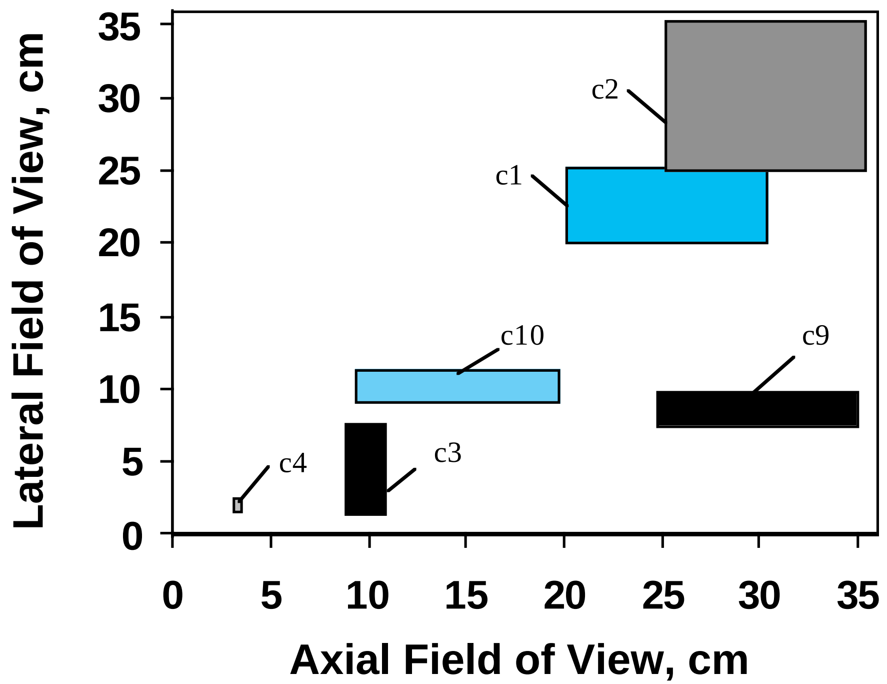


Figure C9b

- ***Req. C9 - IR Imaging (cont.)***

Facing figure shows the distribution and range of parameters of lateral and axial field of view for infrared imaging which define the envelope required to accommodate the basis experiments presented in this document.

Infrared Imaging



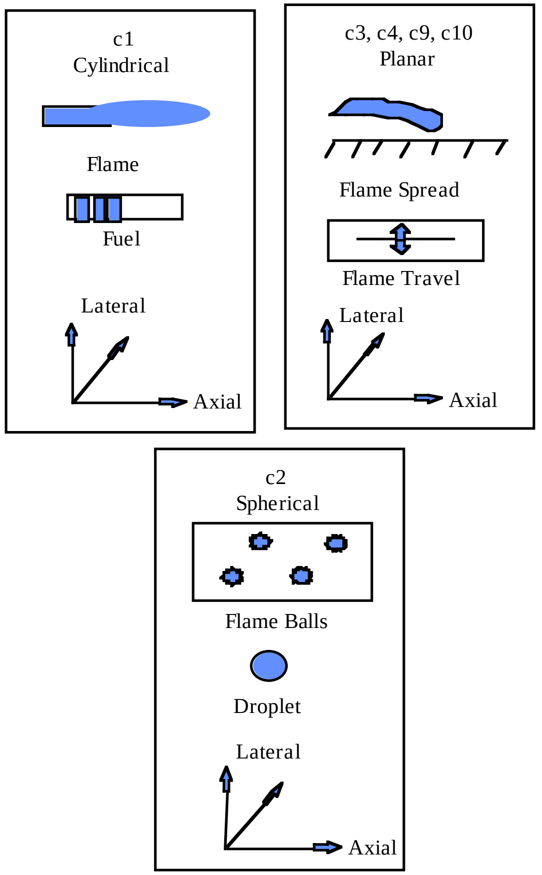


Figure C9c

- ***Req. C10 - UV Imaging***

  The FCF shall provide imaging systems, power, control and data acquisition capabilities for imaging in the ultraviolet spectrum (nominally 250 to 400 nm). Framing rates to 100/sec are required. Requirements are shown in Figures C10a-c.

Images of the combustion region in the ultraviolet spectrum provide information on the spatial distribution of the hydroxyl radical, OH, which emits at 310 nm. This image serves to define the reaction region of the flame.

As above, important parameters associated with these images are field of view, depth of field, spatial resolution, and framing rate. The ranges of these parameters required for the basis experiments are displayed in the following graphs and serve to define envelopes. The "axial" direction refers, again, to the direction of flame propagation or fuel flow.

- ***Des. DC10.1***

  It is desirable to accommodate framing rates to 1,000/sec for UV imaging.

Suggested Techniques: High resolution intensified imagers with imaging wavelenths in the range of 250 to 400 nm. Extended wavelength range intensified imagers may also be utilized for imaging in the visible spectrum as noted for Req. C8.

Facing figure shows the distribution and range of parameters for resolution and frame rate for ultraviolet imaging which define the envelopes required to accommodate the basis experiments presented in this document.

Ultraviolet Imaging

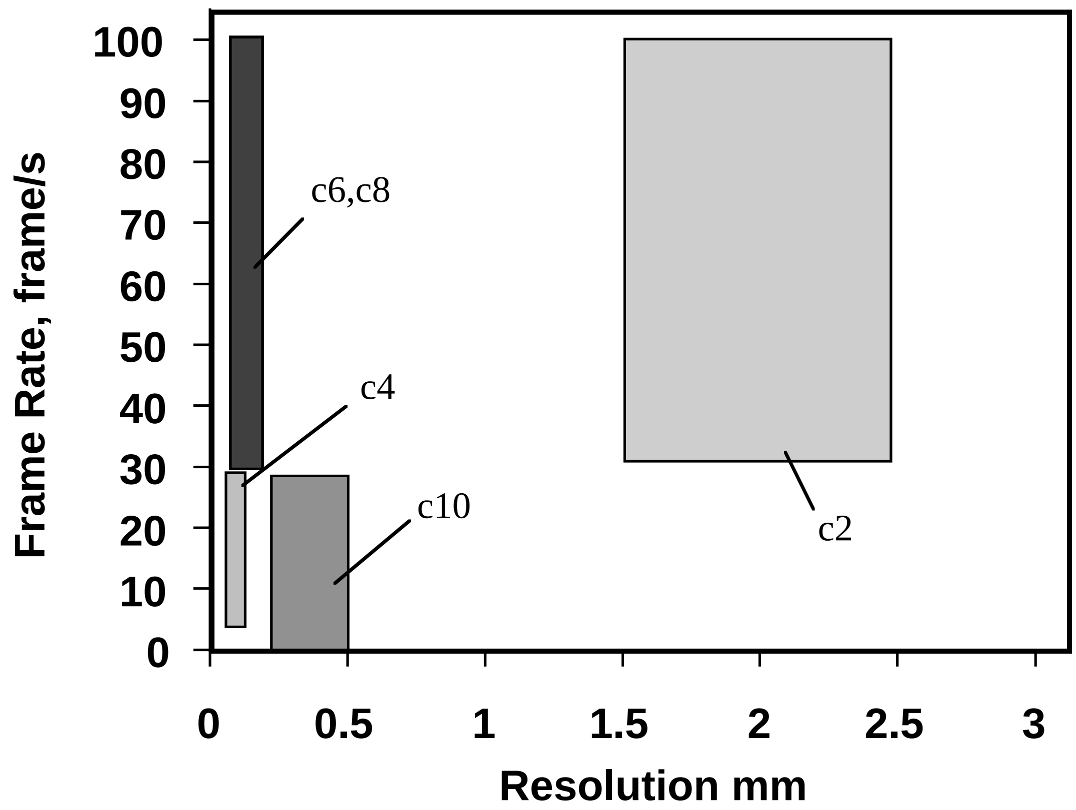


Figure C10a

- ***Req. C10 - UV Imaging (cont.)***

Facing figure shows the distribution and range of parameters of depth of field and field of view for ultraviolet imaging which define the envelope required to accommodate the basis experiments presented in this document.

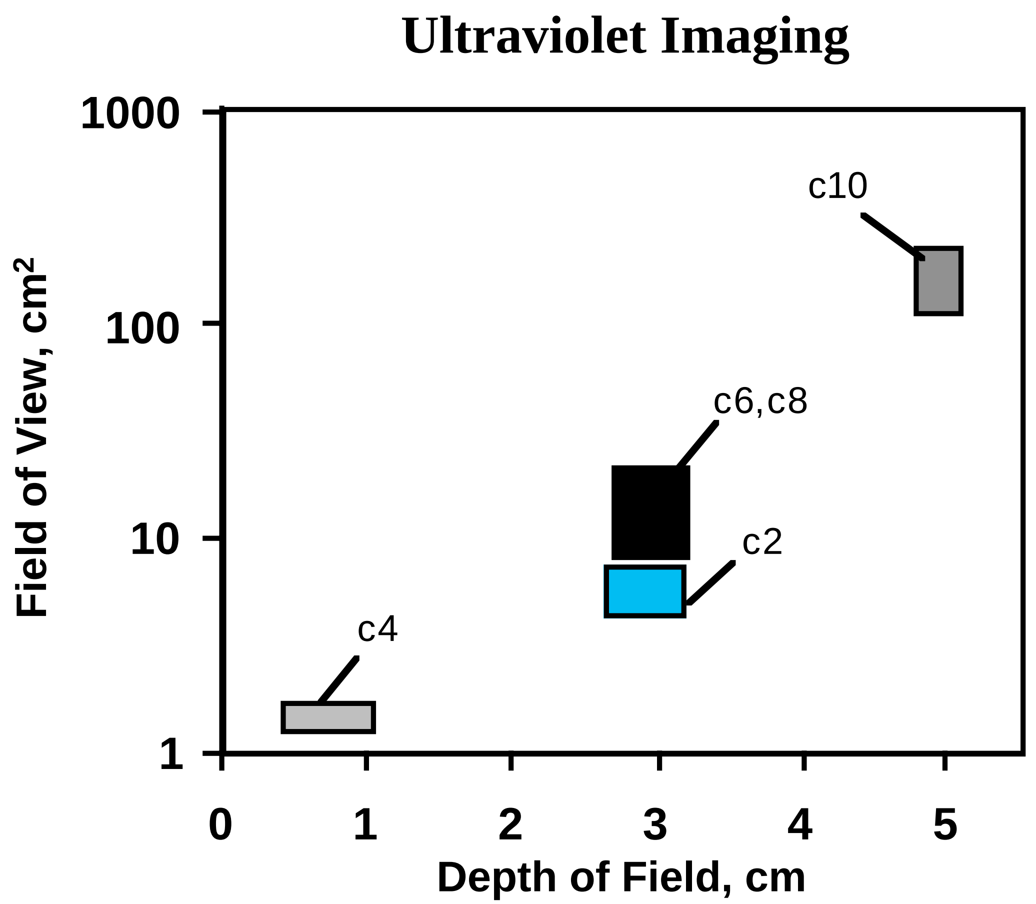

Ultraviolet Imaging
1000
100
10
1
0
1
2
3
4
5
Field of View, cm²
Depth of Field, cm
c10
c6,c8
c2
c4

Figure C10b

-
- ***Req. C10 - UV Imaging (cont.)***

Facing figure shows the distribution and range of parameters of lateral and axial field of view for ultraviolet imaging which define the envelope required to accommodate the basis experiments presented in this document.

Ultraviolet Imaging

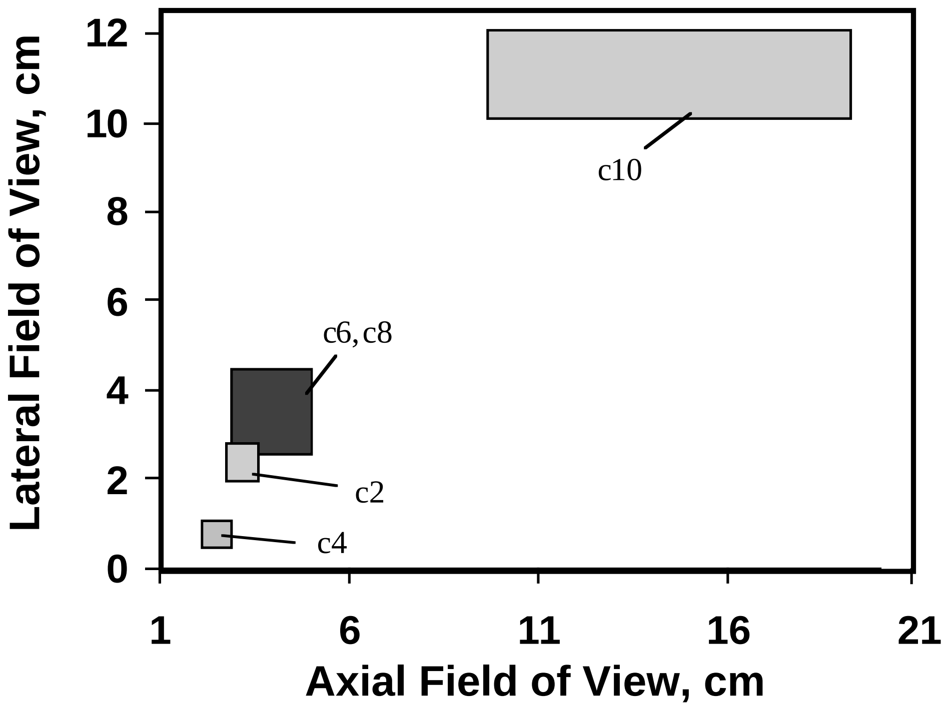
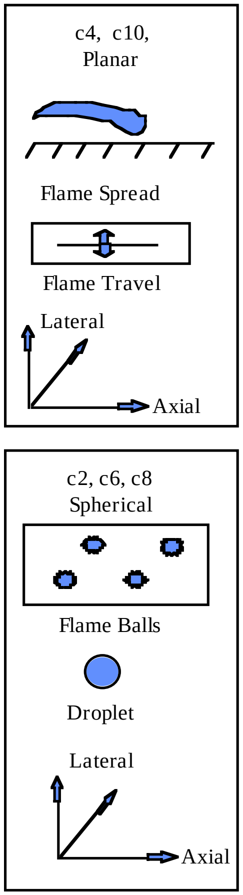


Figure C10c



3.3.1 Evolution of the Thermodynamic State

- ***Req. C11 - Temperature Point Measurements***

  The FCF shall provide power, control and data acquisition capabilities for making multi-point temperature measurements in the gaseous and condensed phases during the course of experiment operations. Up to 12 temperature measurements in the gas phase and up to 20 temperature measurements in the condensed phase are required. Measurements shall be sampled at selectable rates to 1,000 samples per second in the gas phase and to 30 samples per second in the condensed phase. The temperatures in the gas phase range from 280 to 2,000 K and, in the condensed phase, range from 200 to 1,100 K. Requirements are shown in Figures C11a-d.

Point measurements of temperature in the gas phase provide spatially and temporally-resolved information on heat generation and heat transfer during the combustion process. Measurements are made in the flame region and outside the combustion zone.

Point measurements of temperature in the condensed phase provide spatially and temporally resolved information on heat generation and heat transfer during the combustion process. Measurements are made on the surface of the fuel and at in-depth locations to obtain conduction rates.

Important parameters associated with these measurements include number of sensor locations, sampling rate, temperature range, and measurement accuracy. The ranges of these parameters required by the basis experiments are displayed in the following graphs and serve to define envelopes for this requirement.

Suggested Techniques: Thermocouples, thermistors, SiC fibers, and Rayleigh scattering techniques. Fine-wire thermocouples may be used for high sampling rates in the gas phase (on the order of several hundred Hz) when flow rates are of sufficient magnitude provided their time constants are measured. Imaging systems provided for Req. C8 to C10 may be utilized.

Facing figure shows the distribution and range of parameters for number of sensor locations and sampling rate for multi-point temperature measurement in the gas phase which define the envelopes required to accommodate the basis experiments presented in this document.

Gas-Phase Temperature - Point Measurements

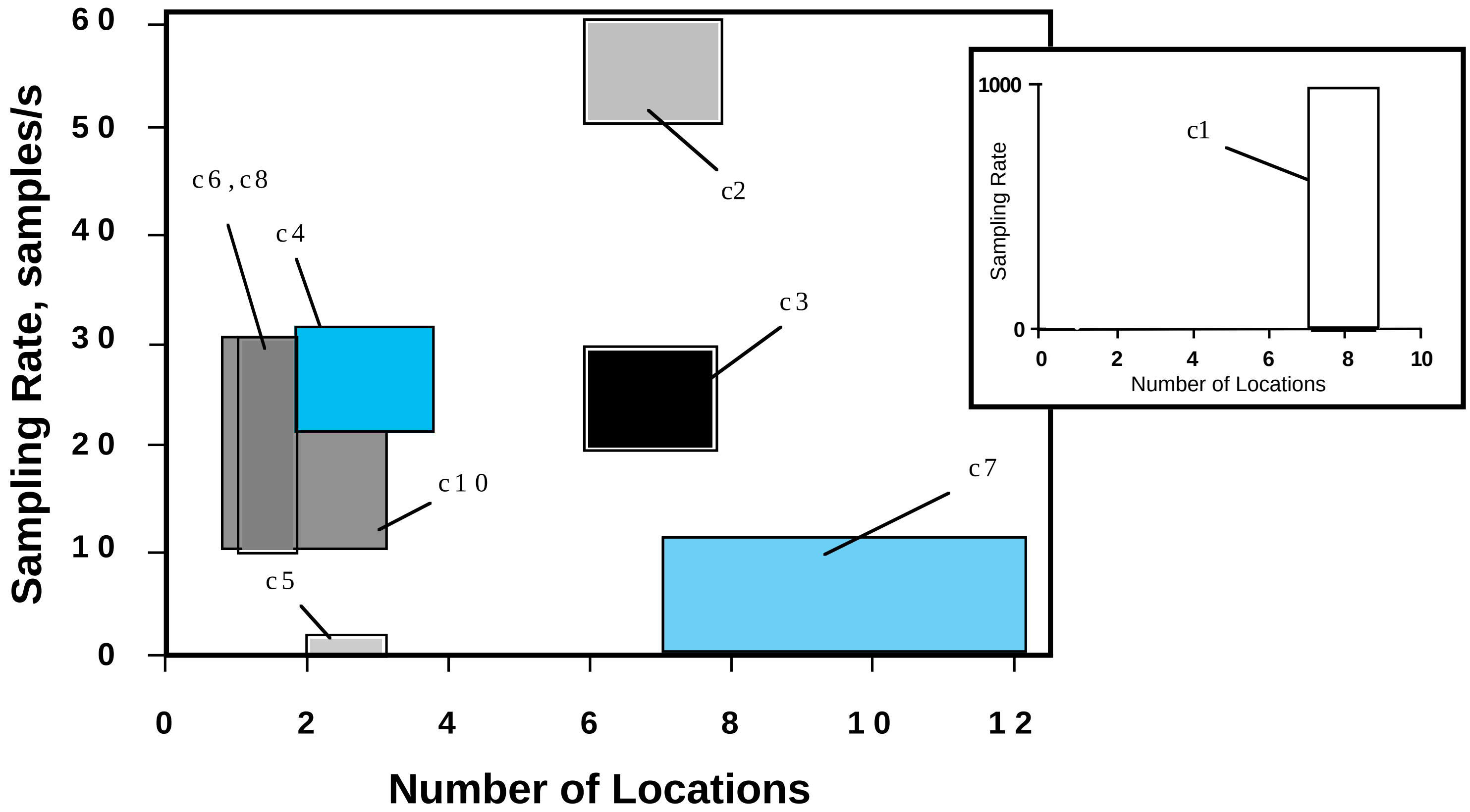


Figure C11a

- ***Req. C11 - Temperature Point Measurements (cont.)***

Facing figure shows the distribution and range of parameters for temperature range and measurement accuracy for multi-point temperature measurement in the gas phase which define the envelopes required to accommodate the basis experiments presented in this document.

Gas-Phase Temperature - Point Measurements

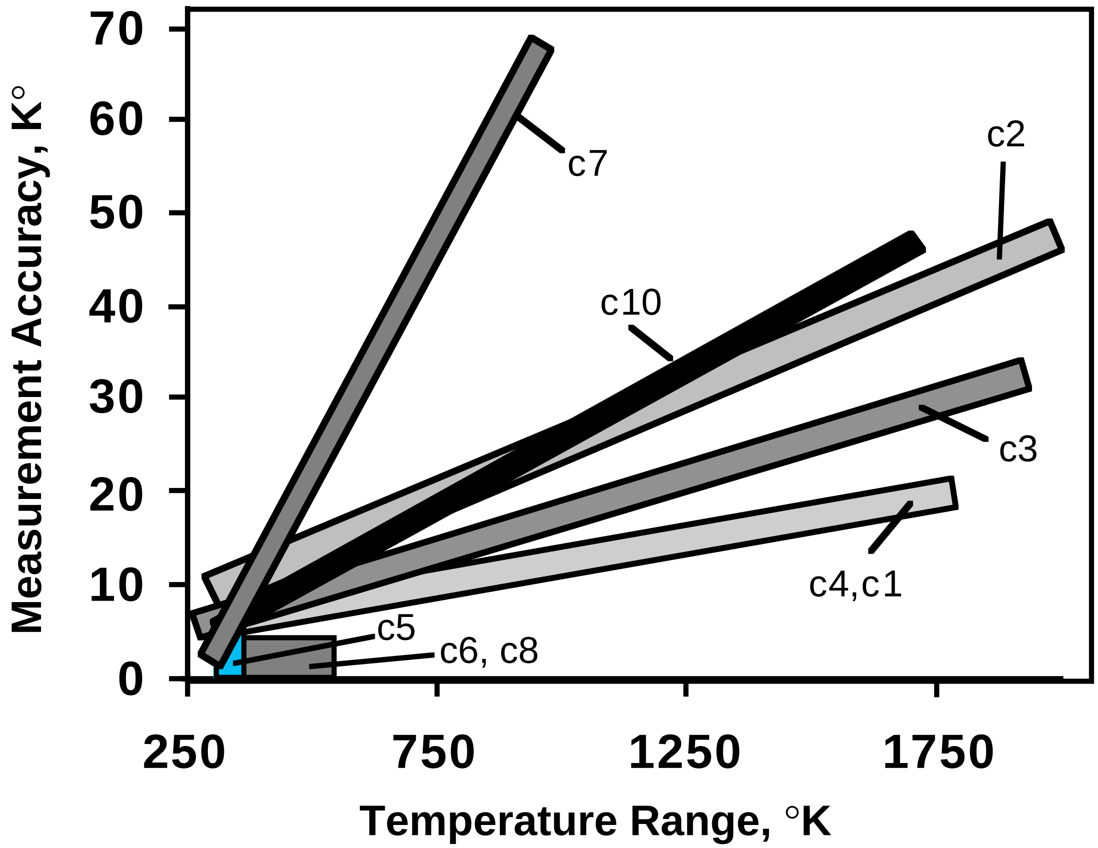


Figure C11b

- ***Req. C11 - Temperature Point Measurements (cont.)***

Facing figure shows the distribution and range of parameters for number of sensor locations and sampling rate for multi-point temperature measurement in condensed phases which define the envelopes required to accommodate the basis experiments presented in this document.

Condensed-Phase Temperature - Point Measurements

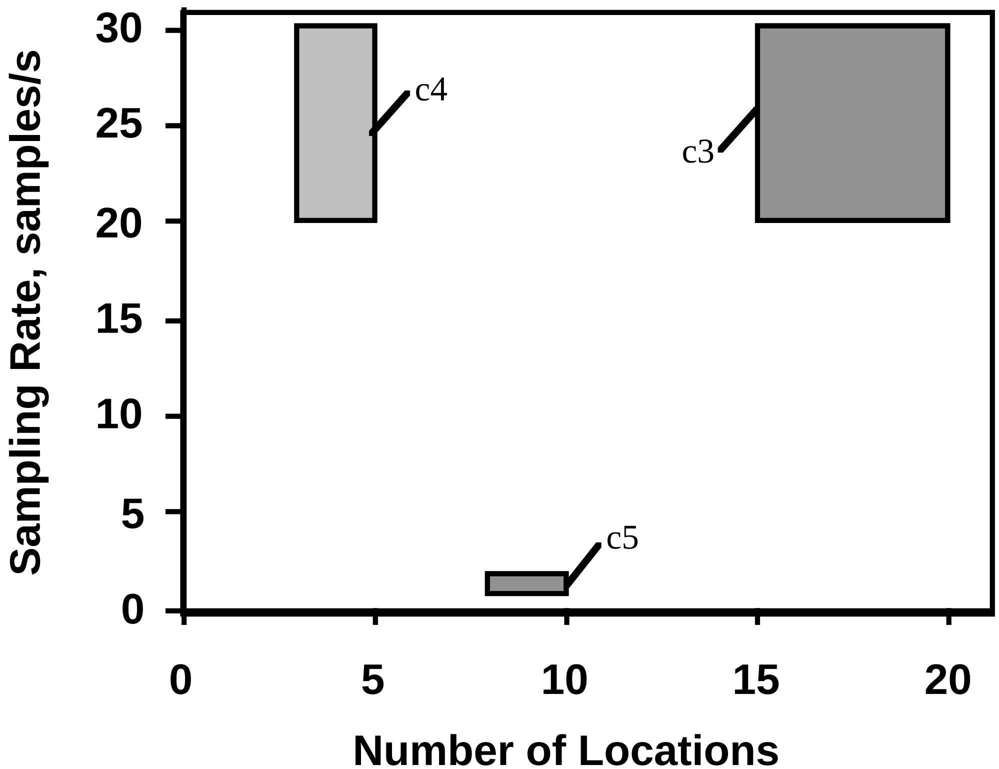


Figure C11c

- ***Req. C11 - Temperature Point Measurements (cont.)***

Facing figure show the distribution and range of parameters for temperature range and measurement accuracy for multi-point temperature measurement in condensed phases which define the envelopes required to accommodate the basis experiments presented in this document.

Condensed-Phase Temperature - Point Measurements

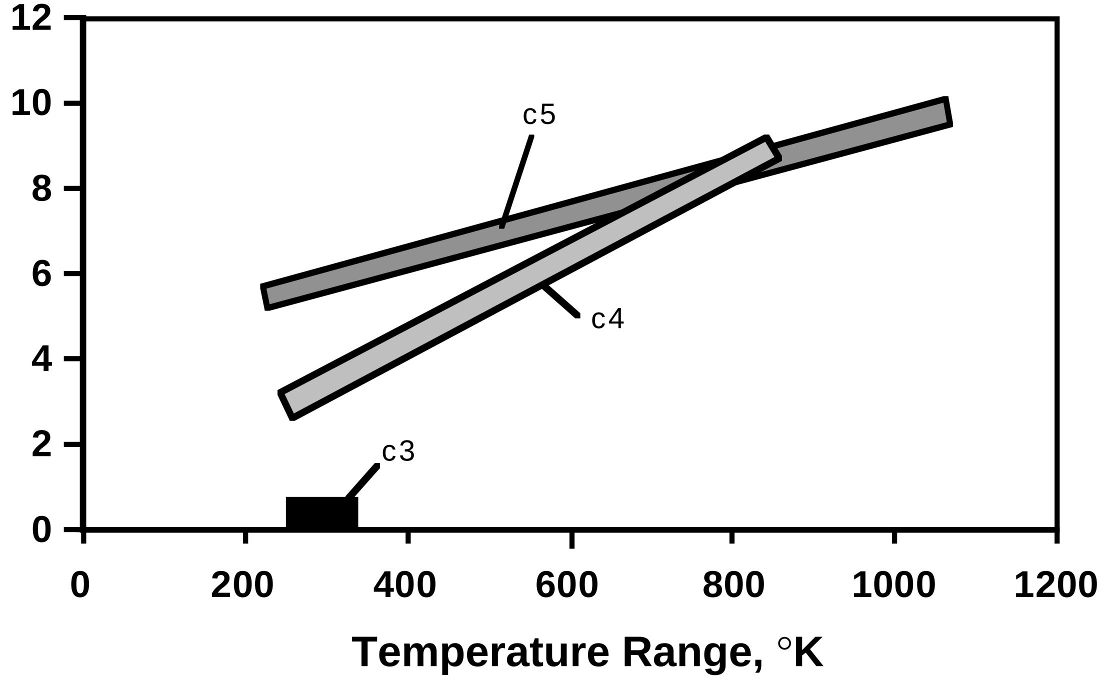


Figure C11d

- ***Req. C12 - Temperature Field Measurements***

  The FCF shall provide power, control and data acquisition capabilities for measuring temperature fields in the gaseous and condensed phases during the combustion experiment operations. Temperature fields may span the range 280 to 2,000 K in the gas phase and 260 to 1300 K in the condensed phase. Sample rate shall be selectable to at least 60 samples/second. Requirements are shown in Figures C12a-f.

Field measurements of temperature enable tracking of the spatial development of temperature with time and provide information on the heat generation and heat transfer caused by the combustion process.

Important parameters associated with these measurements are field of view, spatial resolution, sampling rate, temperature range, and temperature resolution. The ranges of these parameters required for the basis experiments are displayed in the following graphs and serve to define envelopes.

- ***Des. DC12.1***

  It is desirable to accommodate sampling rates to 1,000 samples/second for temperature field measurements.

Suggested Techniques: Schlieren (regular and rainbow), shadowgraphy, interferometry, IR imaging. Imaging systems provided for Req. C8 to C10 may be utilized.

Facing figure shows the distribution and range of parameters for spatial resolution and sampling rate for temperature-field measurement in gas phases which define the envelopes required to accommodate the basis experiments presented in this document. An additional figure is also provided on the following pages.

Gas-Phase Temperature - Field Measurements

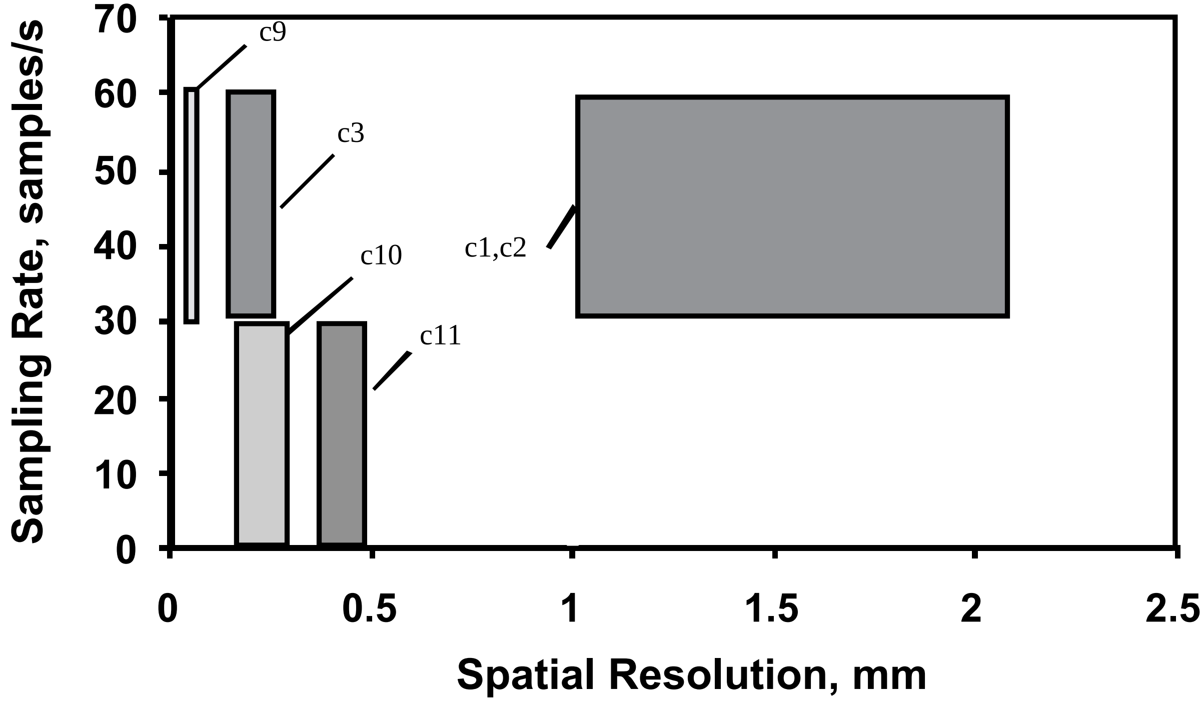


Figure C12a

- ***Req. C12 - Temperature Field Measurements (cont.)***

Facing figure shows the distribution and range of parameters for temperature resolution and range for temperature-field measurement in gas phases which define the envelopes required to accommodate the basis experiments presented in this document. An additional figure is also provided on the following pages.

Gas - Phase Temperature - Field Measurements

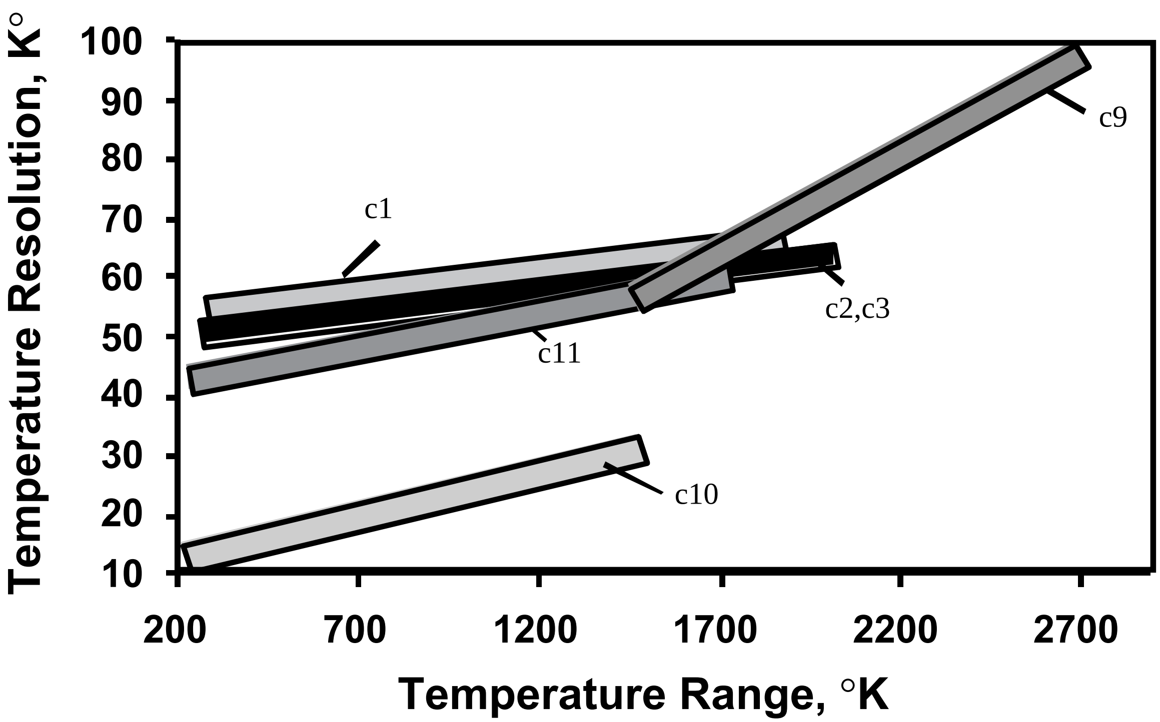


Figure C12b

- ***Req. C12 Temperature Field Measurements (cont.)***

Facing figure shows the distribution and range of parameters of lateral and axial field of view for gas-phase temperature-field measurements which define the envelope required to accommodate the basis experiments presented in this document.

Gas-Phase Temperature - Field Measurements

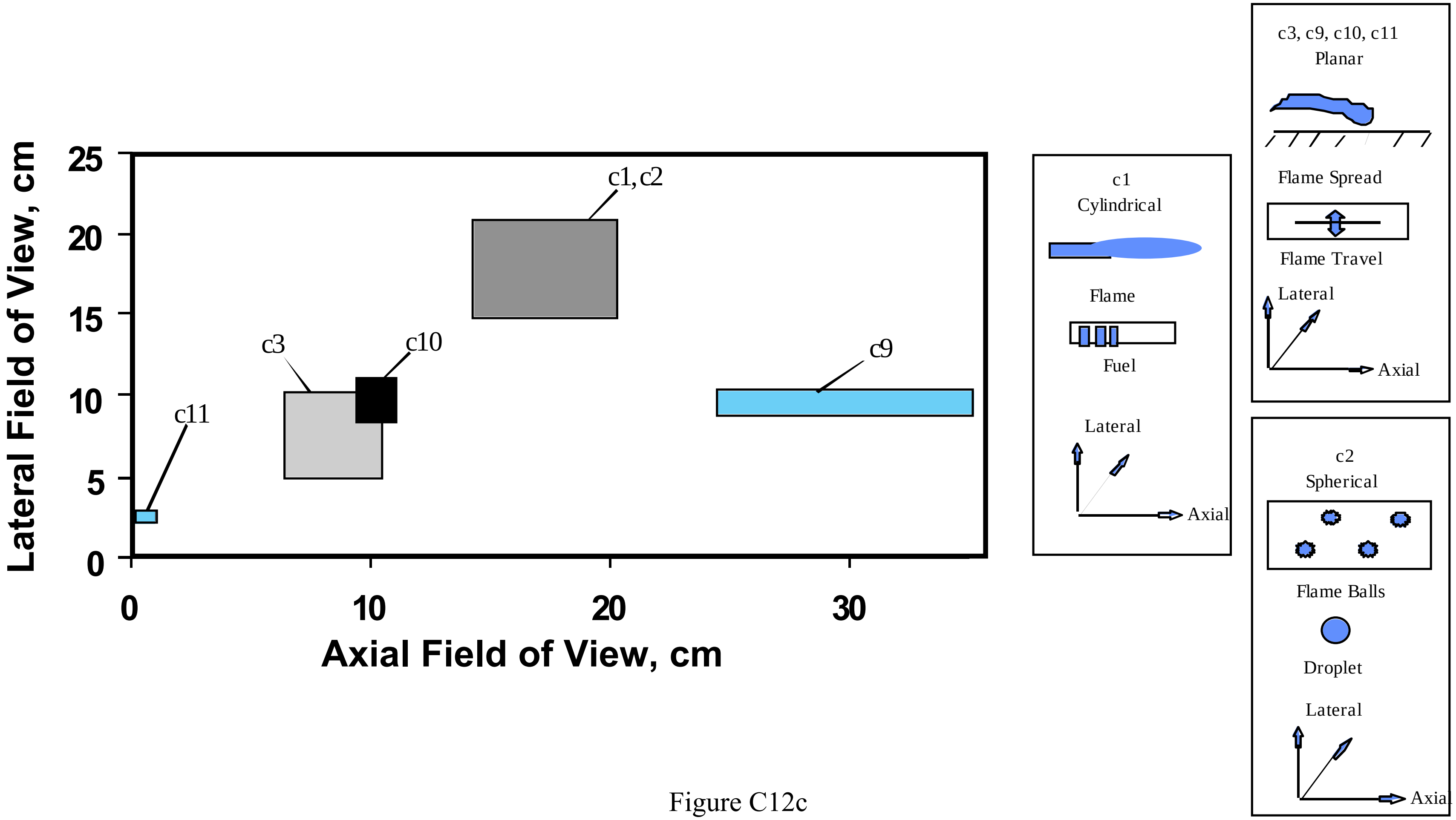


Figure C12c

- ***Req. C12 - Temperature Field Measurements (cont.)***

Facing figure shows the distribution and range of parameters for spatial resolution and sampling rate for temperature-field measurement in condensed phases which define the envelopes required to accommodate the basis experiments presented in this document.

Condensed-Phase Temperature - Field Measurements

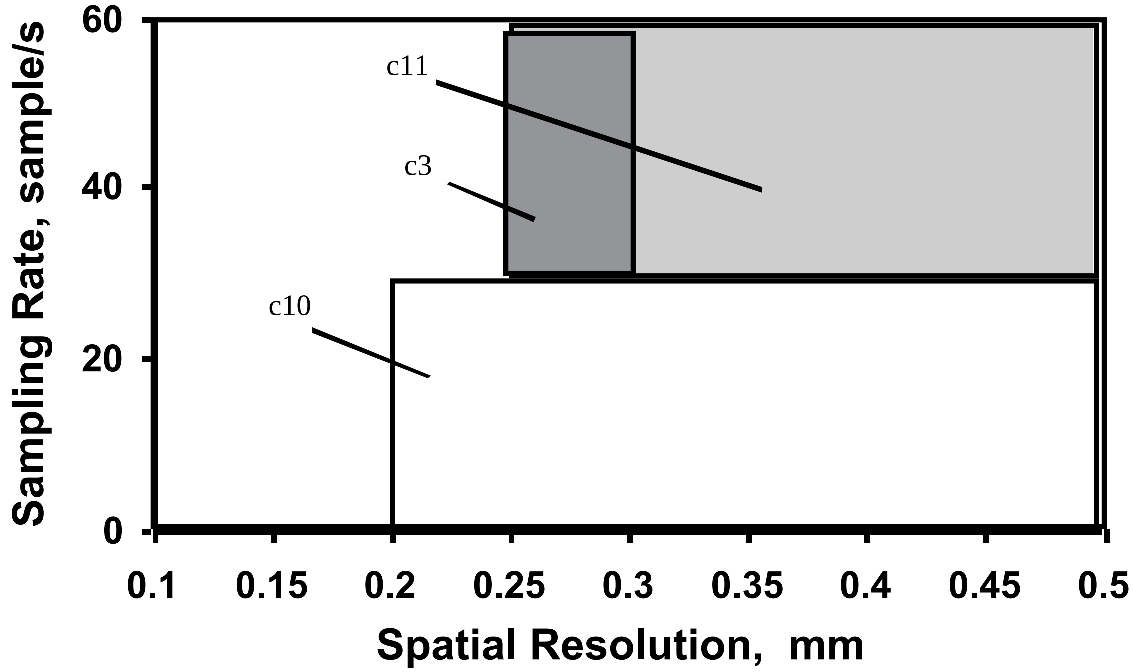


Figure C12d

- ***Req. C12 - Temperature Field Measurements (cont.)***

Facing figure shows the distribution and range of parameters for spatial resolution and sampling rate for temperature-field measurement in condensed phases which define the envelopes required to accommodate the basis experiments presented in this document.

Condensed-Phase Temperature - Field Measurements

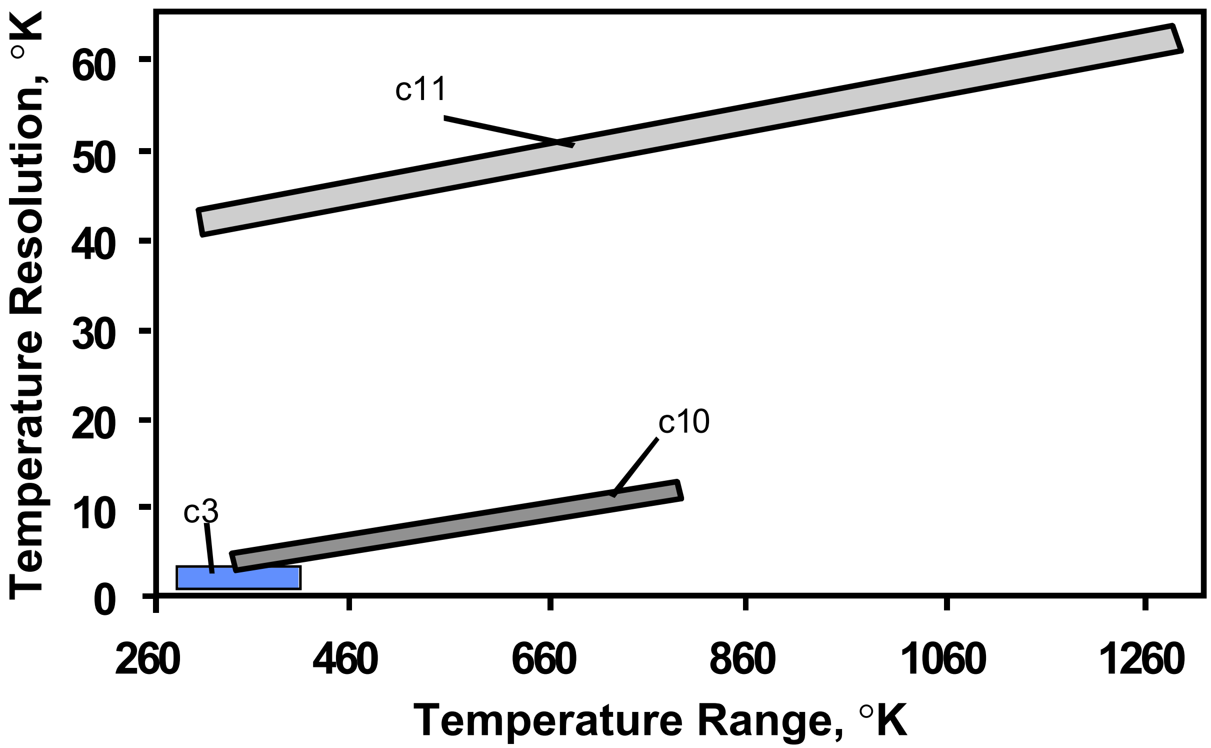


Figure C12e

Req. C12 - Temperature Field Measurements (cont.)

Facing figure shows the distribution and range of parameters of lateral and axial field of view for condensed phase temperature-field measurements (see discussion below) which define the envelope required to accommodate the basis experiments presented in this document.

Condensed-Phase Temperature - Field Measurements

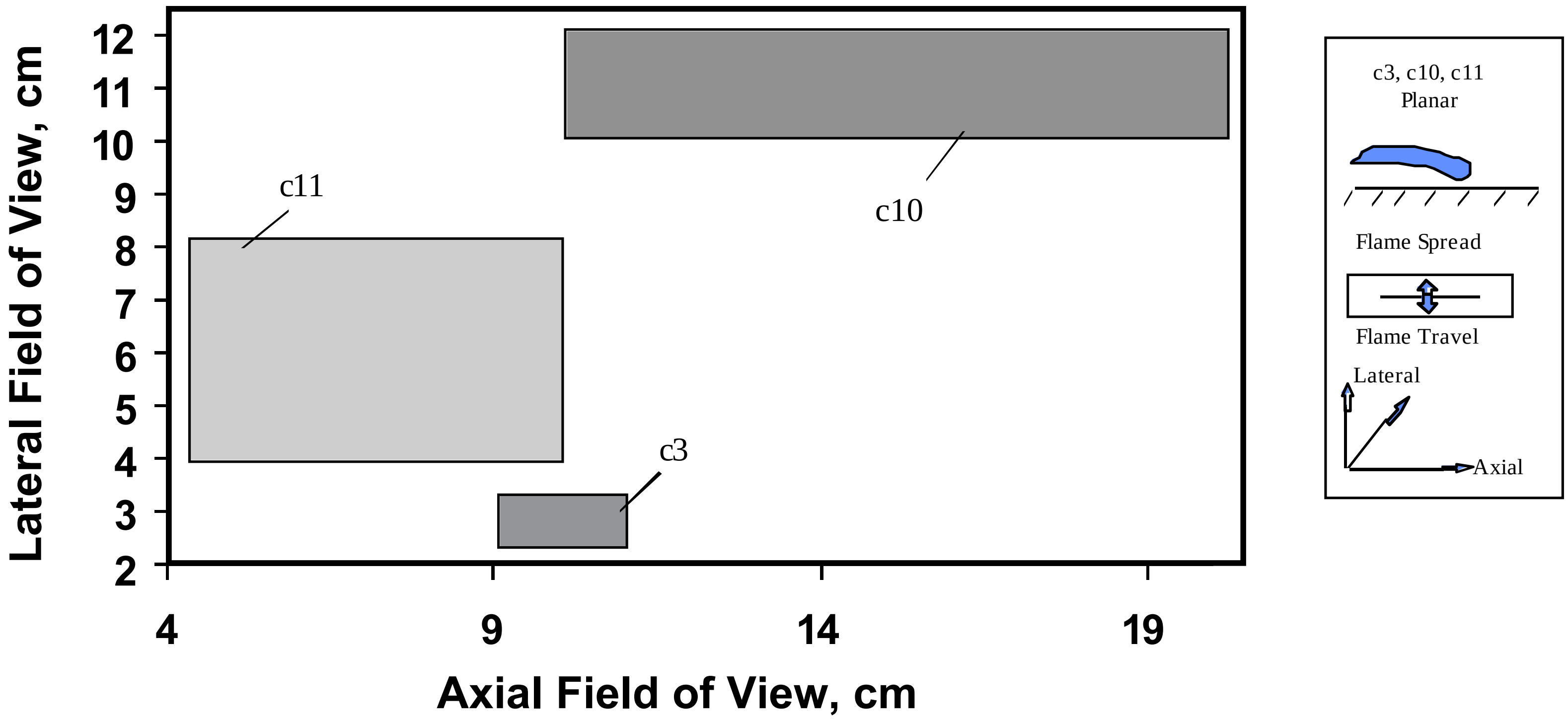


Figure C12f

- ***Req. C13 - Pressure Measurements***

  The FCF shall provide power, control and data acquisition capabilities for measuring pressure of the test section during the course of experiment operations. Pressures may span the range 0 to 10 atm. The FCF shall provide static (less than or equal to 30 Hz) pressure transducers that meet the range and accuracy of the basis experiments. Requirements are shown in Figures C13a-b.

Changes in pressure serve to track the progress of the combustion event. The pressure measurement requirements for the existing basis experiments track, primarily, the pressure changes in the test section.

For experiments which can be carried out in smaller volumes, pressures may span to the range 100 to 150 atm.

The capability to measure both time-averaged and time-dependent pressure must be available. Hence, sample rates shall be selectable to at least 1,000 samples/second. This range will also enable tracking of acoustic phenomena.

Suggested Techniques: Pressure transducers, condenser micro-phones.

Facing figure shows the distribution and data rates of parameters for number of sensors for pressure measurement which define the envelopes required to accommodate the basis experiments presented in this document.

Pressure Measurements

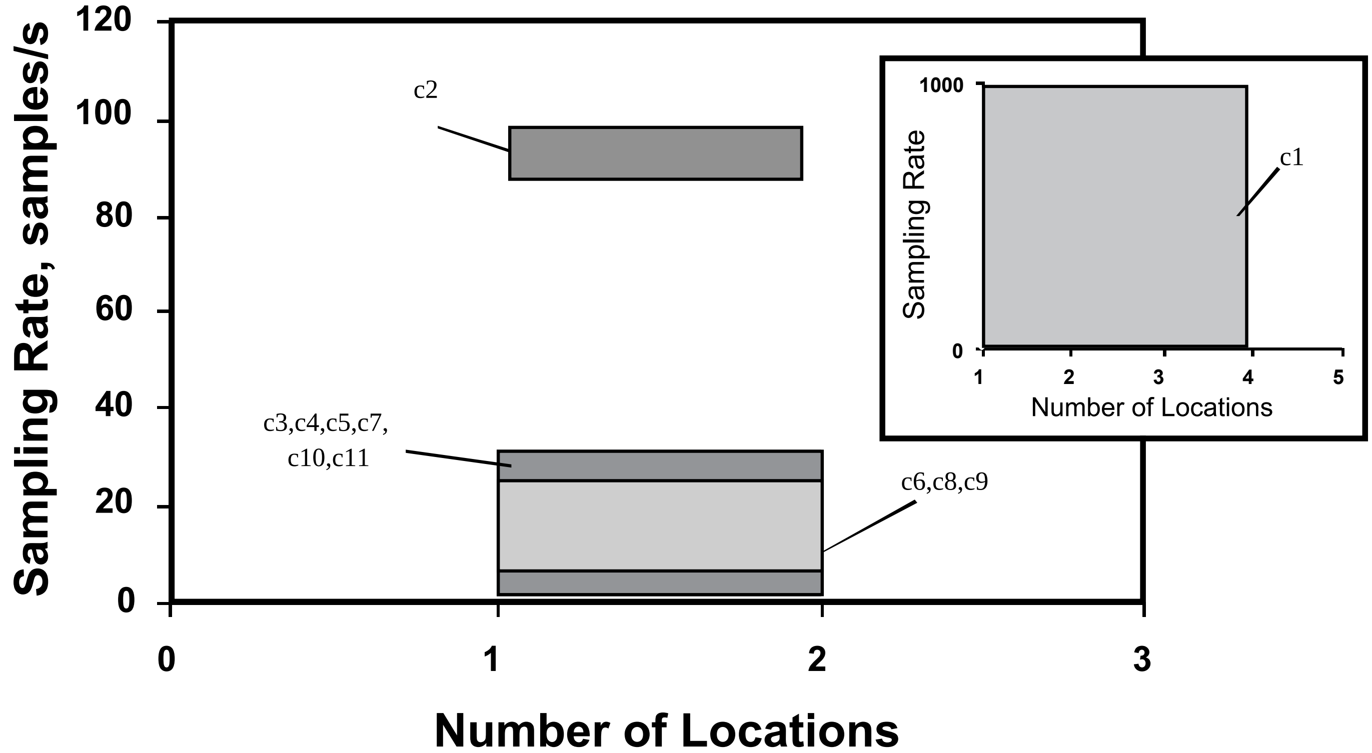


Figure C13a

- ***Req. C13 - Pressure Measurements (cont.)***

Facing figure shows the distributionof accuracy and range for pressure measurement which define the envelopes required to accommodate the basis experiments presented in this document.

Pressure Measurements

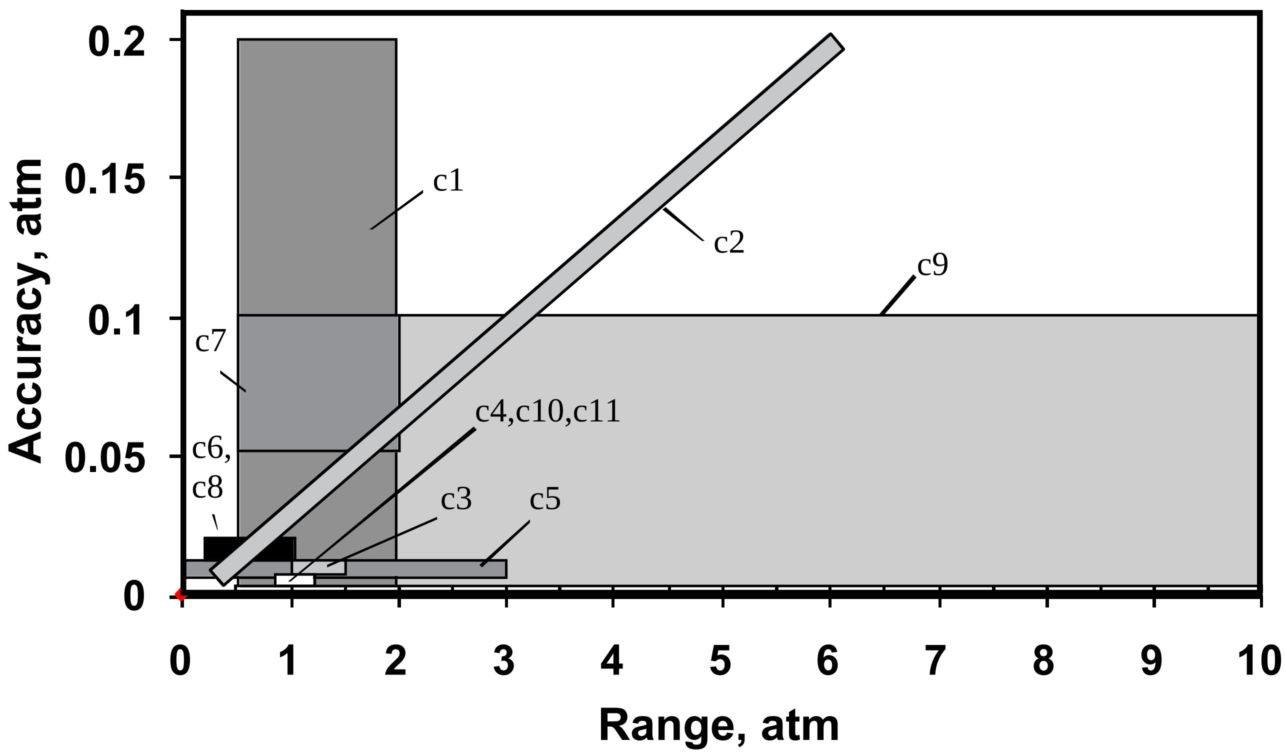


Figure C13b

Req. C14 - Chemical Composition and Soot Measurements

The FCF shall provide sensor systems, power, control and data acquisition capabilities for measuring chemical composition by gas sampling and gas analysis. The components to be measured are hydrogen, methane, propane, oxygen, nitrogen, carbon monoxide, carbon dioxide, sulfur hexafluoride, and water. The range of required measurements shall be 0.1 to 100% by volume with an accuracy of 2% of reading.

The FCF shall provide power, control and data acquisition capabilities for measuring soot volume fraction, soot temperature, and for collecting soot particles in the test section during a combustion experiment. Requirements are shown in Figures C14a-c.

Information provided by chemical composition measurements include completeness of the combustion reactions, chemical kinetic mechanisms, and radiative heat transfer.

Gas analysis shall be feasible for the following components: water, low molecular weight alcohols, ketones, and hydrocarbons.

There is some overlap with the requirements on infrared imaging, since information on spatial distribution of concentrations of radiating species (including soot particles) may be inferred from such measurements.

Soot measurements involve characterizing the soot volume fraction distribution, soot temperature, and soot morphology. Soot volume fraction distribution and soot temperature measurements are required to be non-intrusive. Soot morphology is obtained by study of soot particles obtained from intrusive sampling. Chemical composition measurements can also be used for determining temperatures.

Requirements on soot measurements and chemical composition are shown below in terms of: (1) field of view (lateral vs. axial) for the volume fraction and temperature measurements; (2) resolution (lateral vs. axial) for spatial resolution of the volume fraction and temperature measurements. In addition, for intrusive soot sampling, requirement on number of samples versus number of locations for collection are also shown.

Suggested Techniques: Thermophoretic soot sampling, two color pyrometry, infrared spectroscopic array, laser-induced incandescence, laser-induced fluorescence, light absorption, gas sampling, gas sensors, gas analysis with gas chromatography, and mass spectroscopy. Imaging systems provided for Req. C8-C10 may be utilized.

Facing figure shows the range of parameters for number of samples and number of locations for soot measurements which define the envelope required to accommodate the basis experiments presented in this document. Additional figures are on the following pages.

Soot - Volume Fraction, Temperature and Morphology

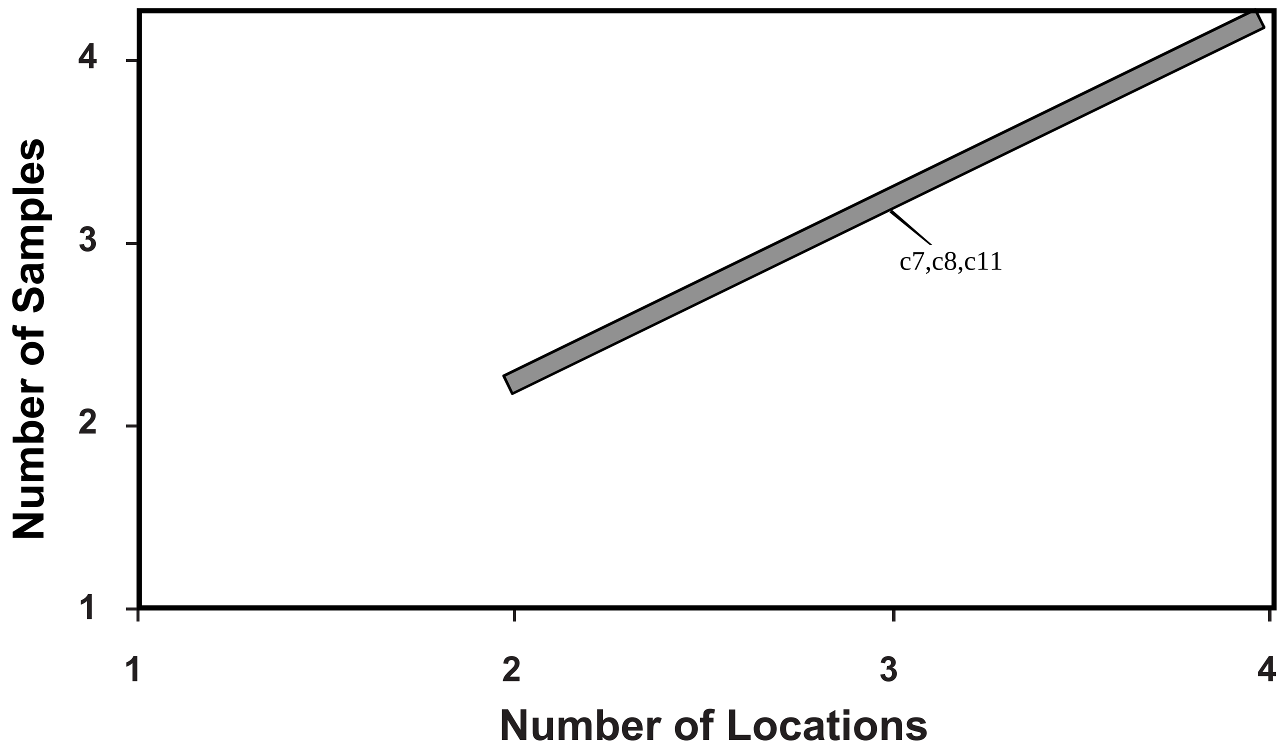


Figure C14a

- ***Req. C14 - Chemical Composition and Soot Measurements (cont.)***

Facing figure shows the range of parameters for axial and lateral imaging resolution for soot measurements which define the envelope required to accommodate the basis experiments presented in this document. An additional figure is on the following pages.

Soot-Volume Fraction, Temperature and Morphology

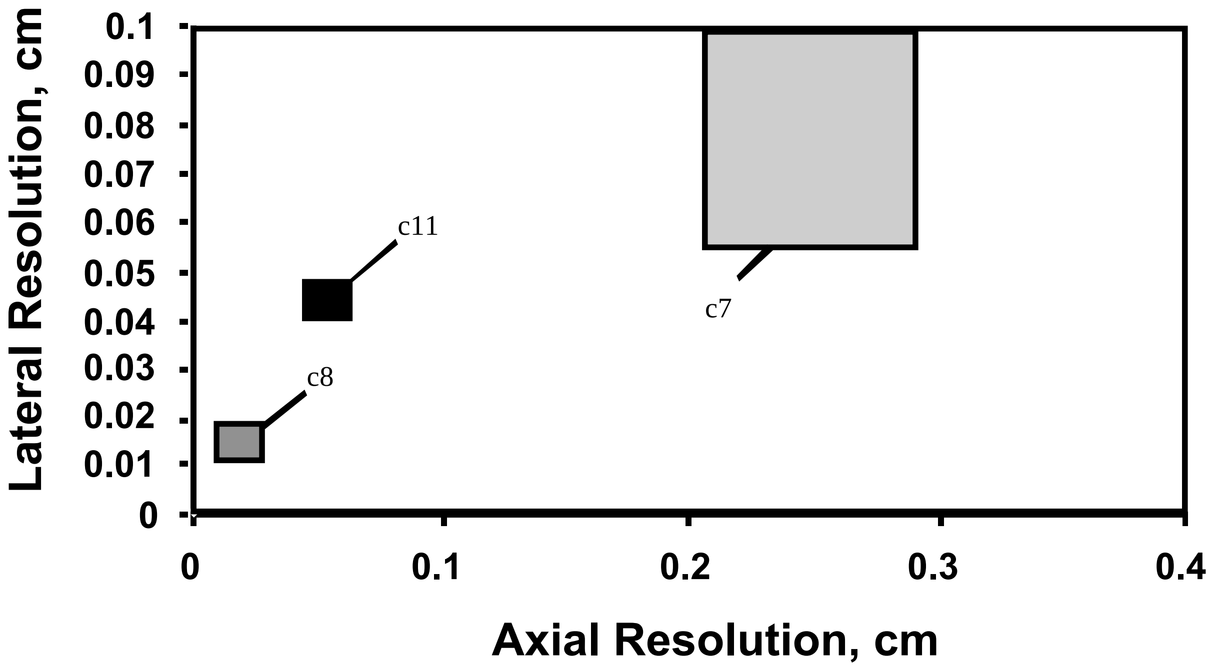


Figure C14b

- ***Req. C14 - Chemical Composition and Soot Measurements (cont.)***

Facing figure shows the distribution and range of parameters for lateral and axial field of view for soot measurement, which define the envelope required to accommodate the basis experiments presented in this document.

Soot-Volume Fraction, Temperature, and Morphology

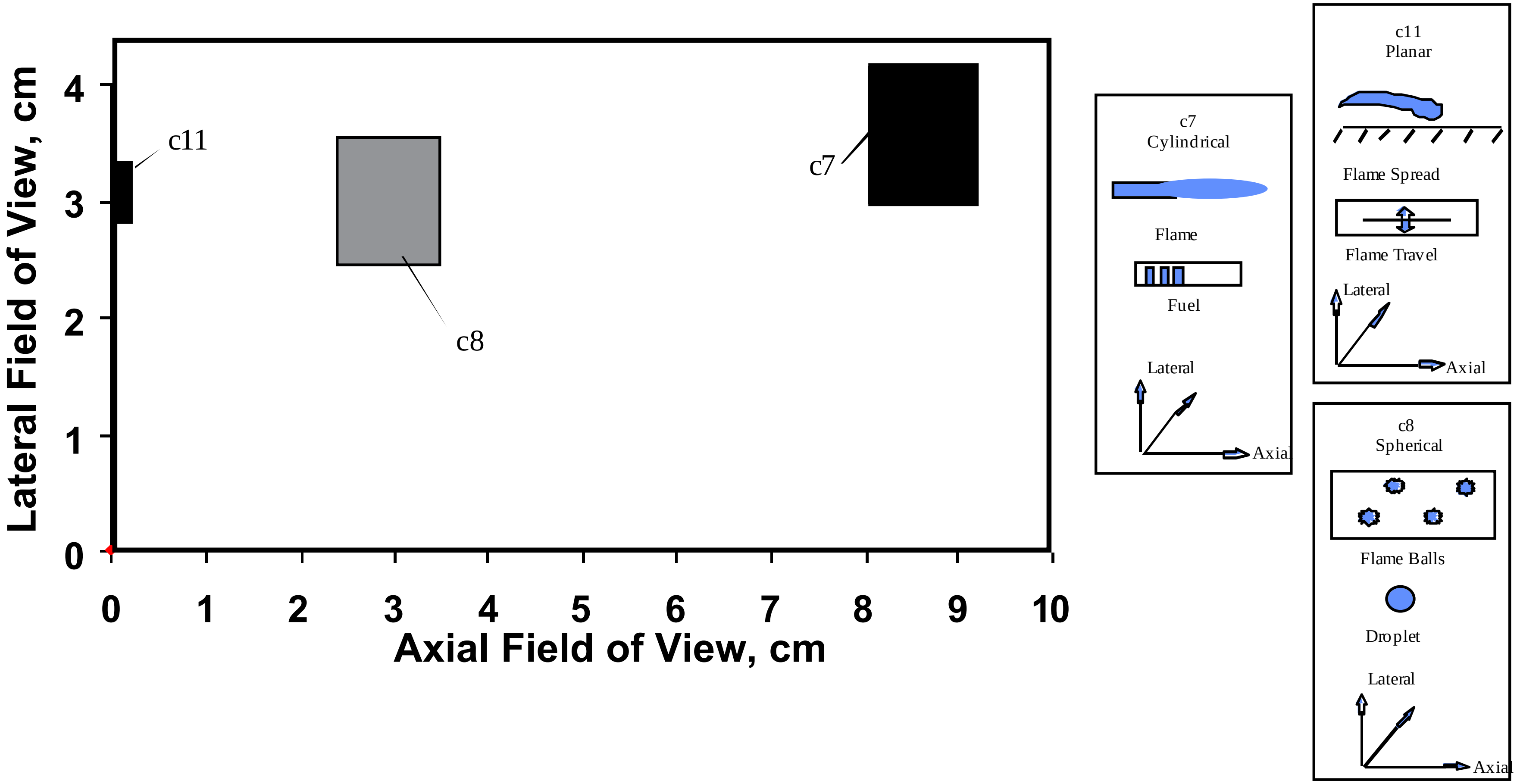


Figure C14c

- ***Req. C15 - Radiometry***

  The FCF shall provide power, control and data acquisition capabilities for measuring radiated energy in the spectral range 200 to 40,000 nm during the combustion experiment. Requirements are shown in Figure C15.

Radiometric measurements provide information on the thermal field and radiative losses from the combustion region. The typical wavelengths of interest are in the range of 0.2 to 40 microns. The field of view is variable with most experiments and the radiometric setup is expected to be integrated with experiment-specific assemblies.

Suggested Techniques: Radiometers, photodiodes.

Facing figure shows the distribution of number of sensors and sampling rates which define the envelope required to accommodate the basis experiments presented in this document.

Radiometry

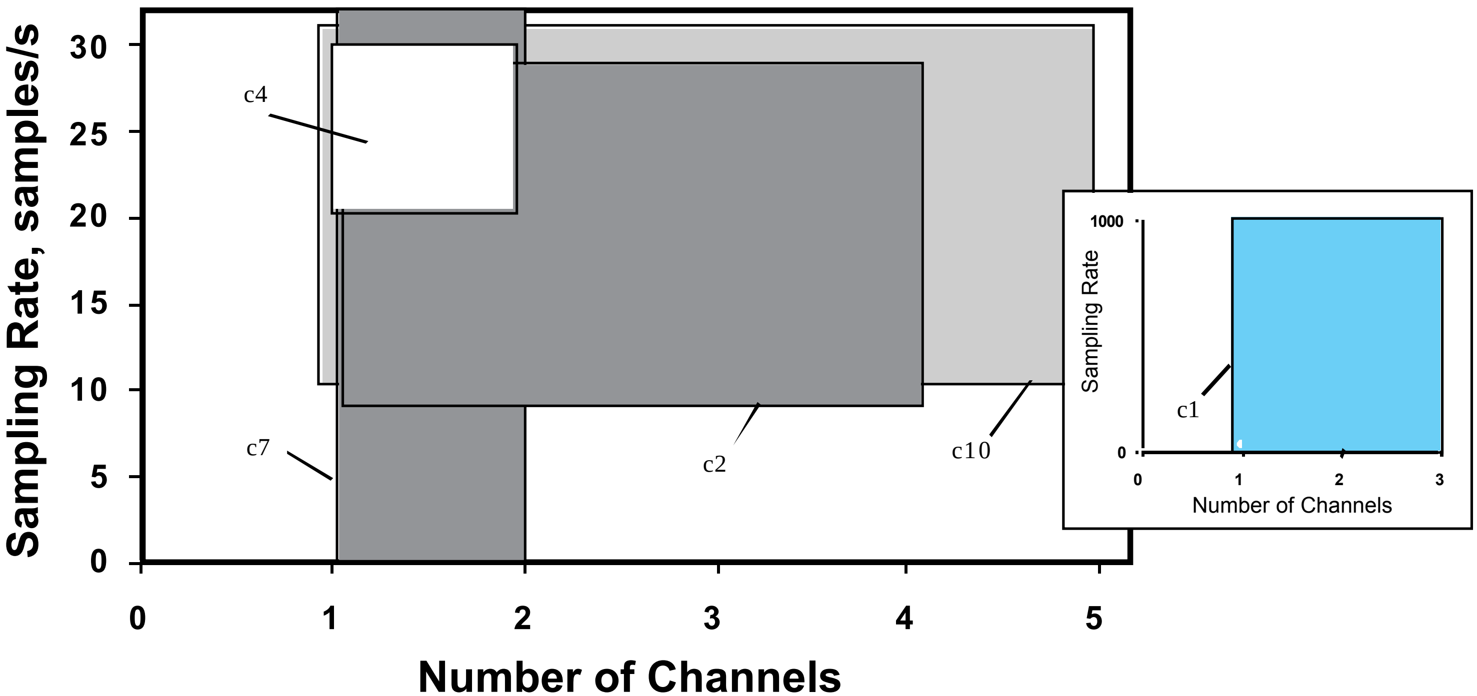


Figure C15

3.3.3 Evolution of the Fluid Dynamics

- ***Req. C16 - Velocity Point Measurements***

  The FCF shall provide power, control and data acquisition capabilities for measurement of gas velocity in the test section over the range of 0.5 to 5,000 cm/second. Measurements shall be made at selected locations (1 to 20) in the test section and sampled at rates from 2 to 1,000 samples/ second. The FCF shall accommodate the exhaust of seeding particles. Requirements are shown in Figures C16a-b.

Velocity measurements serve to verify the flow conditions of the experiment and also the velocities that are attained during the evolution of the combustion experiment.

Suggested Techniques: Hot film and hot wire anemometers, pitot static probes, LDV.

Facing figure shows the distribution of sensor count and sampling rates for velocity point measurements which define the envelopes required to accommodate the basis experiments presented in this document.

Velocity - Point Measurements

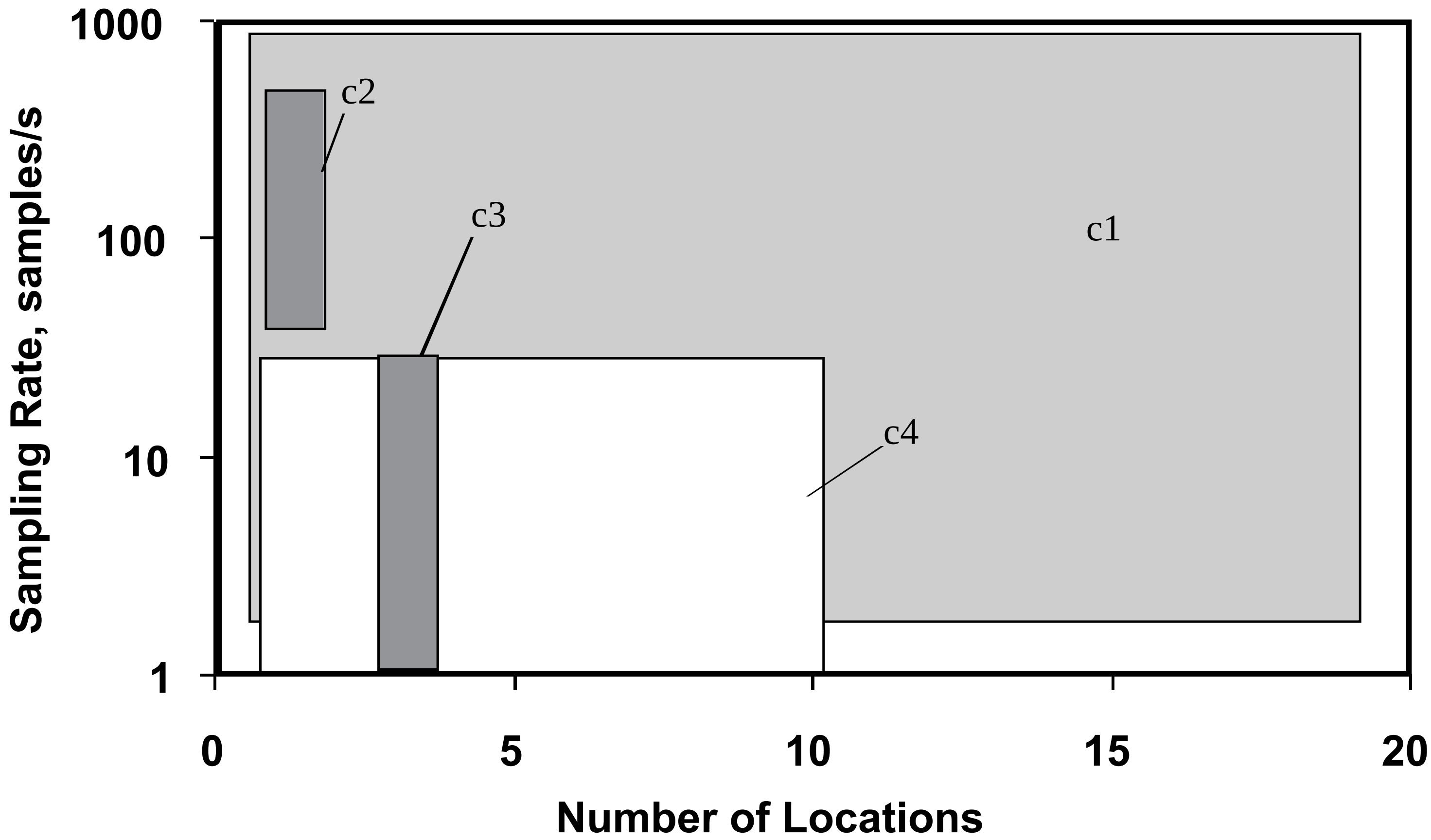


Figure C16a

- ***Req. C16 - Velocity Point Measurements (cont.)***

Facing figure shows the distribution velocity range and precision for velocity point measurements which define the envelopes required to accommodate the basis experiments presented in this document.

Velocity - Point Measurements

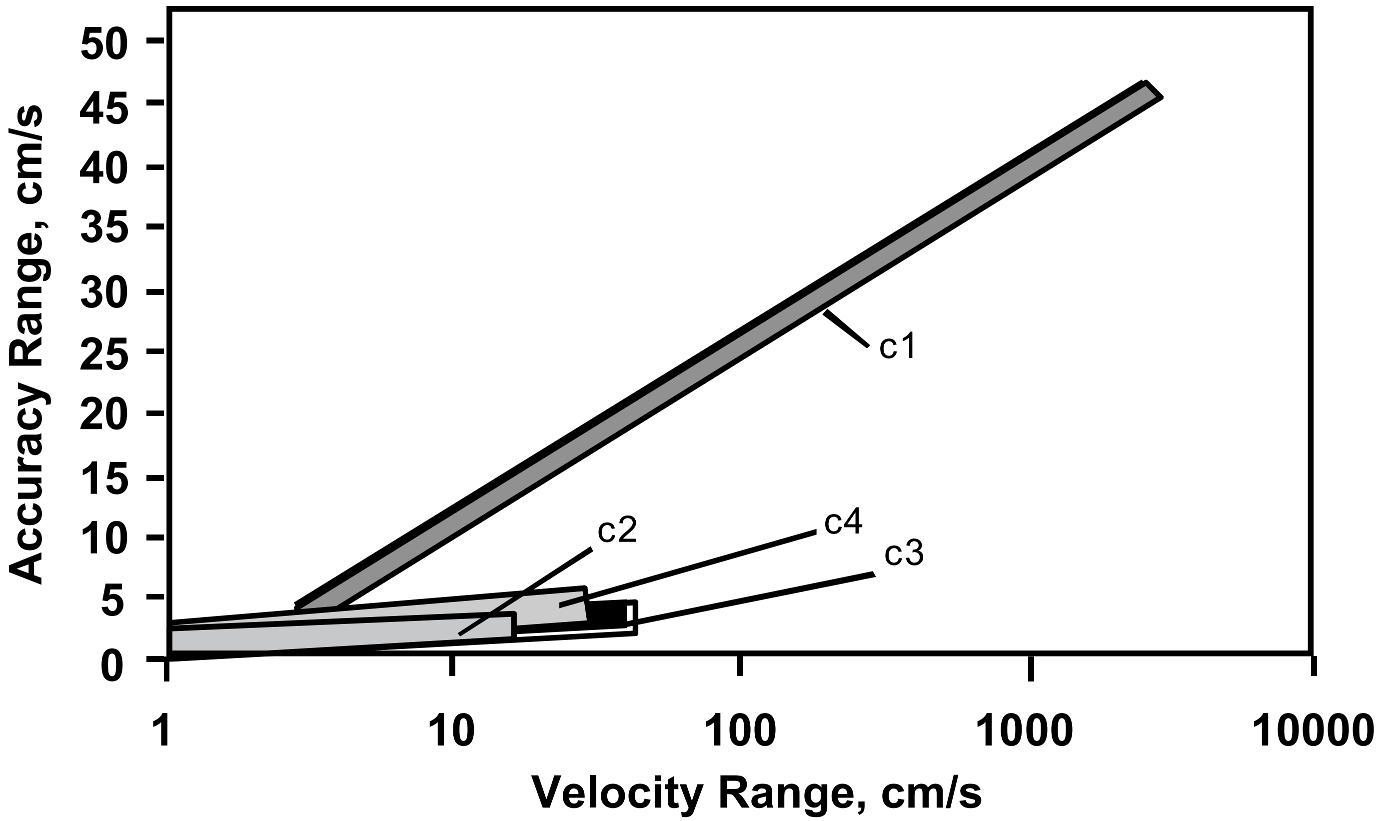


Figure C16b

- ***Req. C17 - Full Field Velocity Imaging***

  The FCF shall provide power, control and data acquisition capabilities for full field imaging of velocities in the gas and liquid phases. Measurements shall encompass the required fields of views and be imaged at rates of 30 to 60/ second. The FCF shall accommodate the exhaust of seeding particles. Field of view requirements are shown in Figure C17.

These measurements provide information on the flow patterns that develop during the combustion event. The requirements are shown in terms of axial field of view, lateral field of view, and framing rate. It is to be noted that for a given experiment, more than one view (e.g., orthogonal views) may be required.

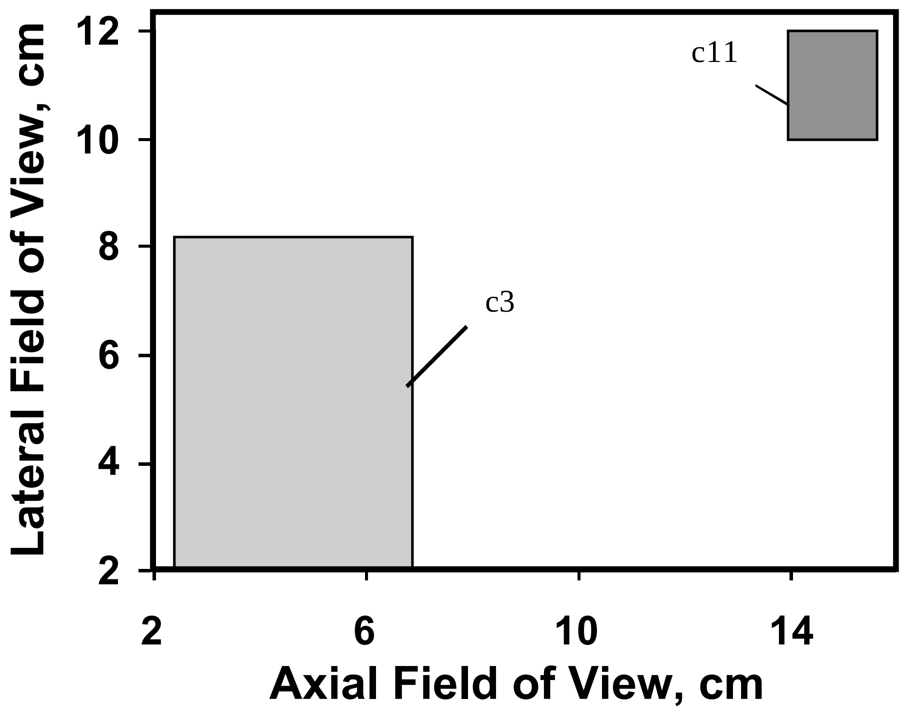
- ***Des. DC17.1***

  It is desirable to accommodate imaging rates to 1,000/second for image-based velocity measurement systems.

Suggested Techniques: Particle imaging velocimetry (PIV) with supporting capabilities for particle dispersal and extraction from fluids, smoke trace visualization. Cameras provided for Req. C8 to C10 may be utilized.

Facing figure shows the ranges of axial field of view and lateral field of view which define the envelope required to accommodate the basis experiments presented in this document.

Full-Field Velocity Imaging (frame rate 30 - 60)



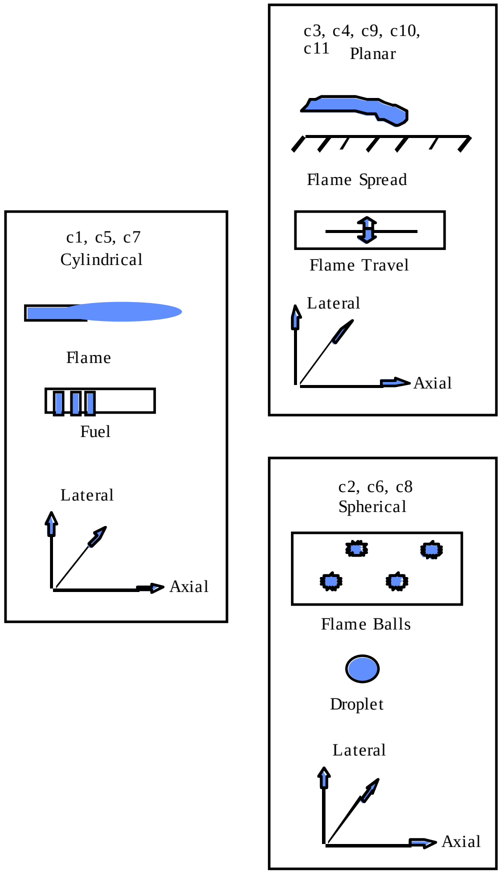


Figure C17

- ***Req. C18 - Acceleration Measurements***

  The FCF shall provide a capability to (typically) monitor residual acceleration and g-jitter over a dynamic range of 10^{-6} to 10^{-2} g/g_0 within the Combustion Facility rack. Specific requirements on frequency and levels will be called out in experiment-specific science requirements, but are expected to fall within the standard parameter range of the Space Acceleration Measurement System (SAMS) accelerometer system. Requirements are shown in Figures C18a-b.

Acceleration measurements serve to verify the acceleration environment of the experiment. Measurements are to be made as close to the experiment as possible. Triaxial measurements are desired.

Suggested Techniques: SAMS accelerometry system.

Facing figure shows the distribution of dynamic range and accuracy which define the envelope required to accommodate the basis experiments presented in this document.

Acceleration Measurements

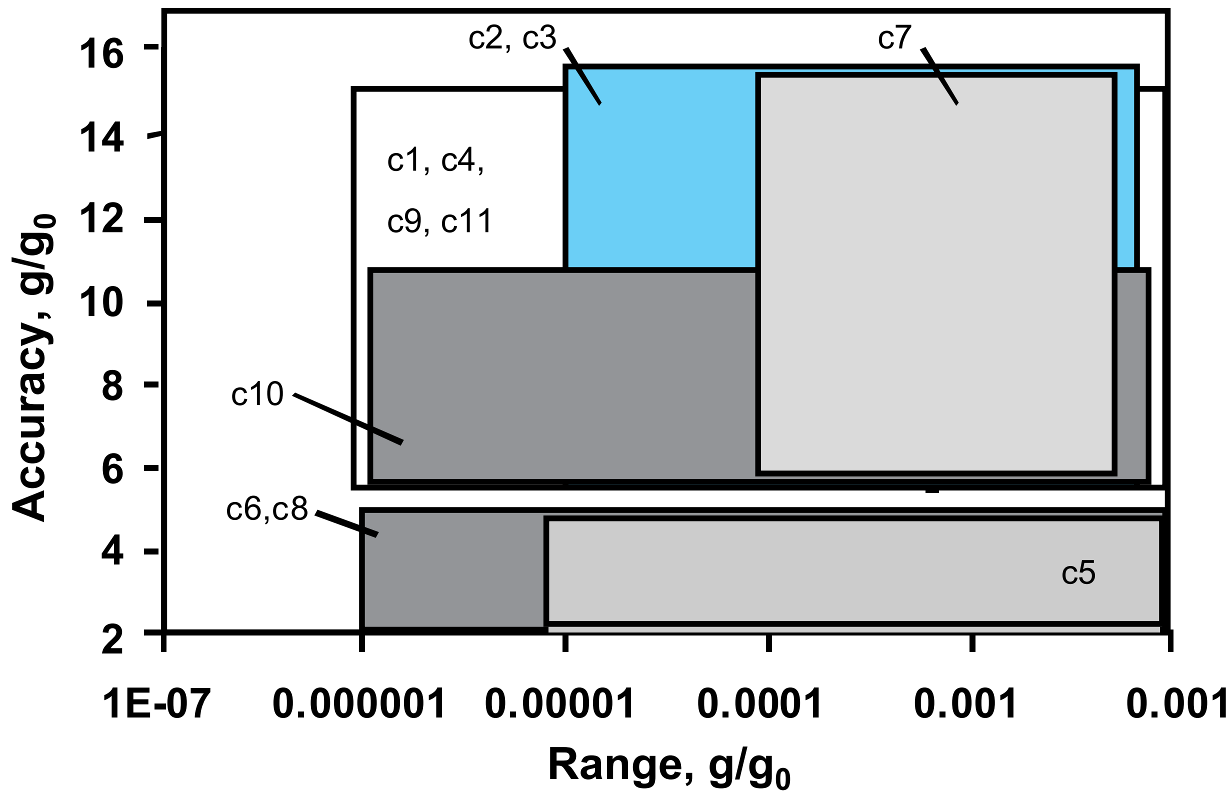


Figure C18a

- ***Req. C18 - Acceleration Measurements (cont.)***

Facing figure shows the distribution of sampling rates which define the envelope required to accommodate the basis experiments presented in this document.

Acceleration Measurements

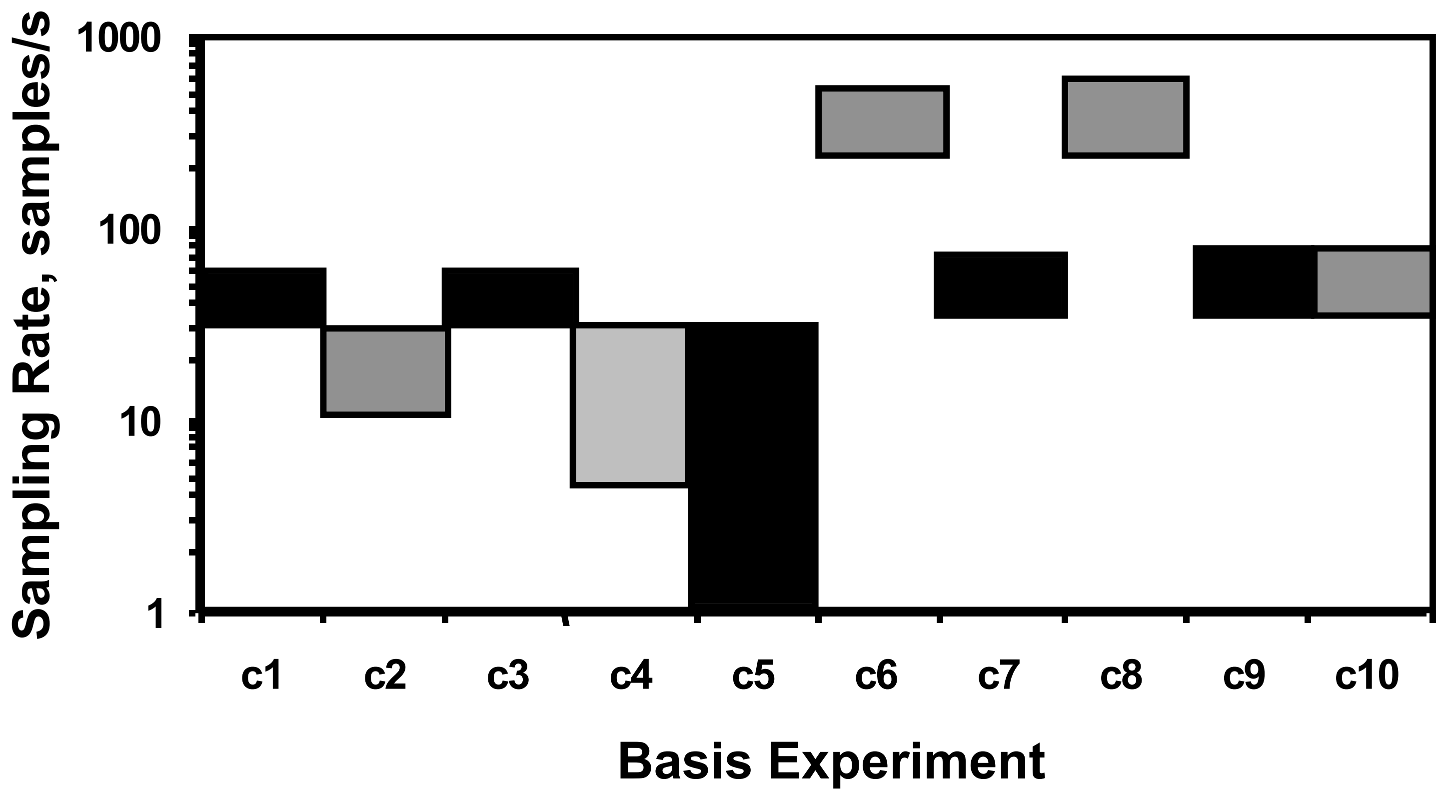


Figure C18b

3.4 DATA MANAGEMENT

The requirements discussed in this section pertain to the acquisition and management of data acquired in the course of the experiment.

- ***Req. C19 - Data Time Resolution***

  The FCF shall provide a capability to time-tag all data streams (including video data). A common clock (relatable to International Space Station events) shall be referenced and digital tags shall permit resolution to 1 second for external events and 0.001 second for experiment events.

Such a capability is required to permit the investigators to correlate a range of measurements within the experiment, as well as correlate experiment activities with external events, such as International Space Station maneuvers or crew activities.

Correlation of video data with other experiment measurements will be of particular importance. Ready identification of video segments for processing and downlink will also be facilitated by appropriate labels and tags.

- ***Req. C20 - Simultaneous Measurements***

  The FCF shall provide, simultaneously, up to eight field measurements and up to 35 single sensor measurements. The FCF shall simultaneously provide the required controls and measurements to operate the PI-specific hardware (required by the science requirements) inside and outside the chamber.

Chapter 4 - FCF Operations Requirements

4. FCF OPERATIONS REQUIREMENTS

4.1 INTRODUCTION

The purpose of this chapter is to specify key elements within the FCF operational processes that directly involve the science team and that impact experiment quality and/or the science throughput of FCF.

As background, one should be aware that human tended microgravity experiments have been conducted in space beginning with the Mercury Program and have been a significant component of Space Shuttle missions since the early 1980s. Over that long history, a considerable amount of experience has been amassed regarding cost effective ways to bring new experiments into being and how to operate them for optimal scientific return.

This chapter distills that previous experience into a small set of requirements, desired capabilities, and goals. The items in this chapter are predominantly based on “expert experience”, rather than directly derived from the basis experiments. None the less, they are of critical importance to the success of the basis experiments, and every effort shall be made to implement them.

The primary interactions of the FCF system with each Principal Investigator (PI) will occur during these three phases of the experiment implementation process:

- **Experiment development** which involves assignment of the experiment to FCF, PI hardware/software development, and training for flight operations.
- **Flight operations** which involve on-orbit set-up and real-time operation of the PI experiment on-orbit using ground systems for “remote control” (telescience).
- **Post-flight operations** which involve distribution and safeguarding of the scientific data and other experiment products.

Consequently, the following FCF operational requirements are grouped into three similarly named sections.

4.2 EXPERIMENT DEVELOPMENT

The development of unique instrumentation to implement PI-specific science requirements (found in the PI SRD) has, historically, been the dominant effort for each new experiment. With FCF, potentially significant savings in cost and schedule may be realized. These benefits will arise because experiment hardware will evolve within a context of existing, verifiable FCF capabilities, rather than from the traditional “clean sheet of paper”.

The convenience and quality of the experiment development process will be important factors in the success of the individual experiments. Achieving convenience and quality shall be the responsibility of both the PIs and the organization responsible for FCF mission planning and utilization.

- ***Req. O1:***

  The FCF mission planning and utilization organization shall provide and schedule PI team access to FCF simulators for and verification of PI hardware and operations procedures.

These simulators shall be available early in the PI experiment development process and at other times throughout the process. Given the large planned throughput of science on FCF, it is assumed that these simulators will be scheduled for a given PI team for a limited amount of time, and the burden will be on the PI team to make efficient use of that time. The types and availability of simulators are topics that should be covered in the FCF User’s Guide.

- ***Req. O2:***

  The FCF mission planning and utilization organization shall schedule verification activities so that each PI team has time to simulate more than one mission timeline sequence in the flight like configuration.

This requirement may impact the quantity of simulators that must be built to support the FCF PI throughput requirements.

- ***Req. O3:***

  Calibration, verification, and functional test data shall be made available within two weeks to the PI team at completion of each test cycle and shall remain available for at least 90 days following completion of the verification test activities.

- ***Req. O4:***

  Functional performance of facility-provided measurement instrumentation as-integrated with PI team provided hardware shall, typically, be verified in-situ and be traceable to certified reference standards (e.g., temperature, pressure, illumination intensity). As an aspect of this requirement, FCF shall have means to periodically re-verify the functional performance of instruments that will remain on-orbit.

Re-verification may be by inspection, test, or analysis; however, the burden of proof regarding the appropriateness of the chosen method rests with the FCF organization.

4.3 FLIGHT OPERATIONS

Flight operations, as the term is used here, involves those activities usually performed after the PI hardware Pre-Ship Review (PSR). They include shipment of the hardware to the launch site, launch of the hardware, set-up on-orbit, performance of the experiment (telescience), and other activities ending with return of the hardware from orbit. Flight operation activities will, at times, overlap with some experiment development activities and some post-flight activities.

The Flight Operations phase is the realization of the individual PI experiment. As such, it is of great interest to the scientific community. Therefore, the associated processes must reflect science inputs. Most significantly, the perceived “style” of the flight operation processes implemented for FCF will determine the appeal and utility of FCF as a “science laboratory”. Consequently, that “style” will directly affect the levels of utilization and total cost of utilization.

- ***Req. O5:***

  FCF shall routinely monitor primary environmental parameters (i.e., temperature, pressure, humidity, and acceleration) within each FCF rack and provide that data to the PI teams before, during, and after the mission – when stated in approved Science Requirements or negotiated FCF operating agreements.

Such data, from prior missions, provided before the subject mission, can be critical to developing an optimized experiment protocol.

- ***Req. O6:***

  FCF shall routinely provide ancillary ISS data (as available from ISS) to the PI teams including information on crew activities, maneuvers, docking, altitude, attitude, etceteras as stated in approved Science Requirements.

For example, ISS activities may perturb the microgravity environment, or the South Atlantic Anomaly may cause an instrument to malfunction. The PI team will need ISS information to mitigate the problem.

- ***Des. DO1.1:***

  It is desirable that FCF shall provide video monitoring (standard video quality) of the crew to the PI team during PI hardware installation, selected operations, and servicing to enable real-time support by ground personnel and to provide a record of the on-orbit crew operations.

- ***Des. DO2.1:***

  It is desirable that FCF shall provide a video monitor for the crew that displays instructions, images, or other supporting data from ground personnel for the purpose of enhancing the efficiency of PI hardware setup, servicing, and operations interactions.

- ***Req. O7:***

  FCF shall provide near-real-time data and at least two imaging channels of downlink and near-real-time command up-link, as specified in the approved SRD, to permit true telescience.

Telescience, as used here, implies that either during or between experiment data points, as required by the experiment protocol, the PI is provided with adequate and timely data to react to unexpected scientific phenomena by timely and beneficial alteration of the experiment protocol. Near-real-time for images shall be less than 15 seconds after the event that was imaged, if required by the experiment. For some experiments, it may be acceptable to downlink a subset of all the images captured (e.g., every 100^{th} image or an image every 15 seconds). Compressed images are not precluded by this requirement, provided that they have adequate resolution and color depth to meet approved science requirements.

- ***Req. O8:***

  FCF shall provide reliable capabilities for recording and protecting science data on-orbit. This capability shall include: Adequate computer memory or other storage media to record all required data from one data point of each active experiment in a time tagged format. Ability to downlink recorded data, limited only by ISS communications bandwidth restrictions on FCF. Clear identification of data existing only on-orbit to assure that no data is accidentally "erased". Ability to transfer data to portable media for return to earth via the Space Shuttle or other transport device.

- ***Des. DO3.1:***

  It is desired that, during a mission, FCF PIs will often be located at their home institution and receive data from their experiment at their home institution. FCF should provide the equipment, software, and operational procedures to permit this. Provisions should be made to distribute all relevant data from a given experiment (including near-real-time science, environment, FCF status, and etceteras as negotiated) to at least 10 PI data terminals spread among at least 3 different PI sites that may be located anywhere.

This desire applies only to PI sites that already possess adequate communications capabilities, and FCF is not expected to provide data communication capabilities to sites that do not already have them in place. However, with the growth of low cost world-wide communications, this should not often be a limitation. It is suggested that this desire be implemented at PI sites using contemporaneous COTS personal computers augmented with FCF provided software, contemporaneous COTS communication software, and contemporaneous commercial networks. Experiment protocols should be designed to operate within any limits normally imposed by the communication network.

- ***Req. O9:***

  FCF shall monitor all essential ISS, FCF, and PI hardware parameters to identify off nominal conditions, communicate such conditions to affected parties, and allow initiation of timely corrective actions that protect the science objectives of operating experiments. In particular, the "quality" of data downlink and command up-link shall be frequently verified.

- ***Req. O10:***

  FCF shall provide both local and remotely located PIs with any custom hardware and software required to display sequential data from FCF sensors (e.g., time, temperature) in tabular or graphical form, and to perform simple statistical transformations on that data (e.g., curve fitting).

It is suggested that the hardware and software be compatible with typical COTS laboratory/office personal computers and software.

- ***Req. O11:***

  FCF shall provide both local and remotely located PIs with any custom hardware and software required to display images acquired by FCF.

It is suggested that the hardware and software be compatible with typical COTS laboratory/office personal computers and software.

4.4 POST FLIGHT OPERATIONS

The "real" work for the science team takes place in the post flight period when data sets are retrieved, data are analyzed, issues with science and hardware are identified, and follow-up experimentation (on-earth) occurs. The timeliness and quality of the final data deliveries is critical to the success of this period.

In addition, it is critical that FCF support the science team, as required, to verify FCF equipment performance or conduct on-earth measurements required to address questions raised by the flight experiment. This could require access to facility equipment (ground support equipment or a functional equivalent of the flight experiment configuration).

- ***Req. O12:***

  FCF shall store on-orbit and subsequently return to the PI team all existing PI-team-provided, experiment-specific equipment, samples, and data utilized or produced during operation of the experiment, per formal pre-flight agreements between FCF and the PI team.

It is suggested that equipment and samples that can remain on-orbit and be used by subsequent PIs should remain on-orbit, at FCF discretion. Equipment and samples consumed during the experiment are exempt.

- ***Req. O13:***

  FCF shall make available to the PI all relevant data generated during flight operations.

These data will include time stamped data files including all measured parameters and images required by the SRD and ancillary data (e.g., accelerometry records, FCF "housekeeping data" such as FCF rack environment data) negotiated in pre-flight formal agreements.

- ***Req. O14:***

  FCF shall identify and fill (as possible) gaps in the negotiated data due to communications outages or equipment failures.

- ***Req. O15:***

  FCF shall provide accesss to all negotiated data for at least 90 days following completion of on-orbit operations.

- ***Req. O16:***

  FCF shall deliver all negotiated data in hard copied format within 60 days following completion of on-orbit operations or within 60 days of return from orbit for data that must be physically transferred to Earth, and FCF shall have one preferred medium and data format(s) for delivery of hard copies.

It is suggested that the medium and format(s) be compatible with contemporaneous 'commercial off the shelf' (COTS) personal computers and software.

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Appendix A - Fluids Basis Experiments

A. FLUIDS BASIS EXPERIMENTS

A.1 INTRODUCTION

Sixteen experiments were selected from the ground or the flight experiment program of the MRD as examples of the breadth of experimental science currently in the Fluids Program and representative of the types of measurement techniques currently demanded by the investigators. The top level requirements for implementing these experiments are used in this document to define the "envelopes" of capabilities called out as requirements on the facility.

In Section A2, brief descriptions of each experiment is provided to enable the reader to sense the types of measurements and range of conditions called out for each experiment.

Facing figure displays the titles and numerology of the basis experiments used in this document to develop the requirements envelopes for the fluids facility.

BASIS EXPERIMENTS FOR FLUID PHYSICS

Section#	Exp.#	Experiment Name	Relevant Area
A2.1	f1	Thin Film Fluid Flows at Menisci	• Interfacial Phenomena/Phase Change
A2.2	f2	Contact Line Hydrodynamics	• Interfacial Phenomena
A2.3	f3	Rheology of Non-Newtonian Fluids	• Complex Fluids
A2.4	f4	Dynamics of Hard Sphere Colloids	• Colloids
A2.5	f5	Colloid Physics	• Colloids
A2.6	f6	Studies in Electrohydrodynamics	• Electrohydrodynamics
A2.7	f7	Nucleation and Growth of Microporous Crystals	• Phase Change/Morphology
A2.8	f8	Interactions of Bubbles and Drops	• Thermocapillarity
A2.9	f9	Thermocapillary Motion of Bubbles and Drops	• Thermocapillarity
A2.10	f10	Interfacial Transport and Micellar Solubilization	• Diffuso-capillary
A2.11	f11	Thermocapillary and Double-Diffusive Phenomena	• Thermo-Diffuso-Capillary
A2.12	f12	Critical Point Phenomena	• Complex Fluids/Phase Change
A2.13	f13	Multiphase Flow Boiling	• Multiphase Flow/Phase Change
A2.14	f14	Mechanics of Granular Media	• Granular Media/Complex Fluids
A2.15	f15	Shear Rheology of Complex Fluids	• Complex Fluids
A2.16	f16	Mesoscopic Studies of Colloids and Complex Fluids	• Colloids

A.2 BASIS EXPERIMENTS FOR FLUID PHYSICS

A.2.1 THIN FILM FLUID FLOWS AT MENISCI (f1)

Key Words: adsorbed film, thin film, thin-thick film, bulk fluid, molecular force evaporation

Goals of Experiment: understand mechanisms of fluid flow and characteristics of fluid spread in a film when the film is heated

Principal Measurements/Observations:

- Imaging of meniscus:
  - Two fields of view required:
    1. full interface (10 x 10 cm field of view; resolution to 100 micron)
    2. close-up of contact line (~20 x 200 micron image; resolution to 1 micron)
  - 30 frame/sec video
- Interferometric measurement of film thickness to ±0.01 micron
- temperature distribution at wall; (and temperature distribution on film surface is required).
- Temperature field spatially resolved to ± 5 micron
- seeded with 5 to 20 micron particles for PIV
- flow velocity distribution within the film (range 0 to 500 micron/sec ±1%); range differs in S and R directions (see figure)
- detect flow velocity or meniscus instability as function of heater power input (power range 0 to 50 Watt ± 0.5 Watt)

Sample Materials: low surface tension fluids (pentane, methanol, acetone, F113)

Test Environment:

- acceleration:
  - quasi-static <1 milli g (if aligned); <1 micro-g (if unaligned)
  - vibratory <10 Hz to be "isolated"
- vector alignment: residual vector in "S" direction
- geometric alignment:
- velocity in "theta direction" must be zero
- thermal:
  - isothermal (20 - 25°C) to ± 0.1°C
- cleanliness:
  - vacuum baked surfaces expected

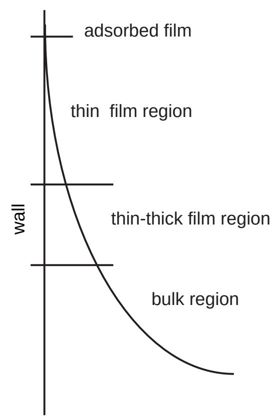
Test Matrix: multiple measurements (5 tests x 2 each; 2 - 3 hour/test) at selected heater powers.

Data Reduction: real-time image processing

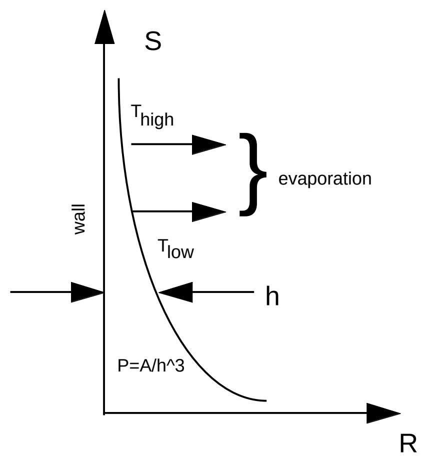
Special Considerations: Steady state evaporation rate needed for each set of measurements. Rate defined by constant wall temperature.

Facing figure shows different thin film regions and expected flows.

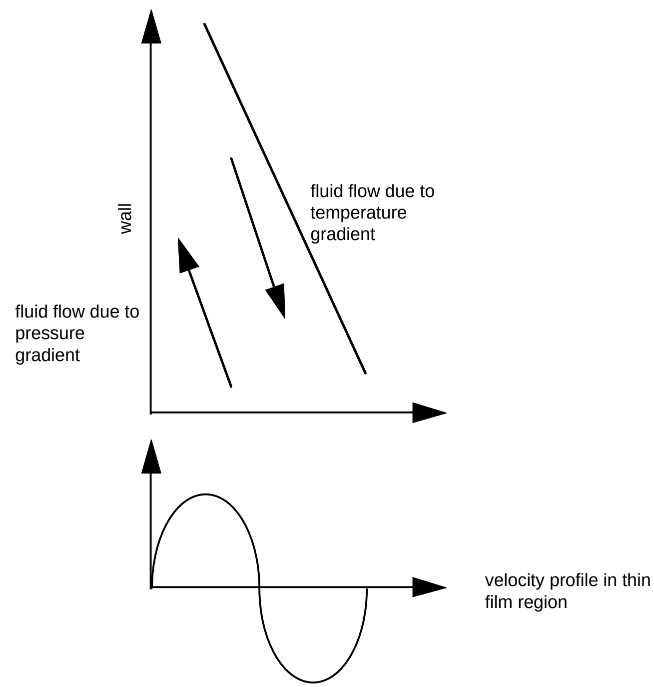
THIN FILM FLUID FLOWS AT MENISCI (f1)



definition of fluid regions



pressure and temperature phenomena in thin film region (thin film region between h of 5 and 20 microns)



expanded thin film region to show how pressure and temperature gradients affect fluid flow (velocity)

A.2.2 CONTACT LINE HYDRODYNAMICS (f2)

Key Words: dynamic contact line, wetting, spreading, contact angle

Goals of Experiment:
- characterize fluid films very close to a moving contact line (a translated boundary)
- characterize flow regions near dynamic contact lines
- examine effects of fluids, cell dimensions, and translation speeds

Principal Measurements/Observations:
- visualization of fluid interface (pinned at outer cylinder and sliding along inner cylinder)
  - two fields of view required:
    1. full interface; 5 to 15 cm field of view; resolution to 100 microns
    2. close to contact line; ~ 2 mm field of view; resolution 2 to 3 microns
  - transient frame rate, 30 fps; steady state, about 1 fps
  - inner surface migrates at rates to 1 mm/sec
- flow visualization (1 to 5 micron tracer particles); and vel. measurement from 3 to 1000 micron/sec +/- 2%

Sample Materials: Silicone fluids (at least 2 fluids varying in viscosity and polydispersity)

Test Environment:
- Acceleration:
  - quasi-static: < 0.1 milli-g
  - vibratory: < 0.1 milli-g for frequencies < 10 Hz
- Thermal:
  - ambient (20 - 25°C) stabilized to ±1°C; resolved to 0.1°C
- Cleanliness:
  - molecular cleanliness at moving surface

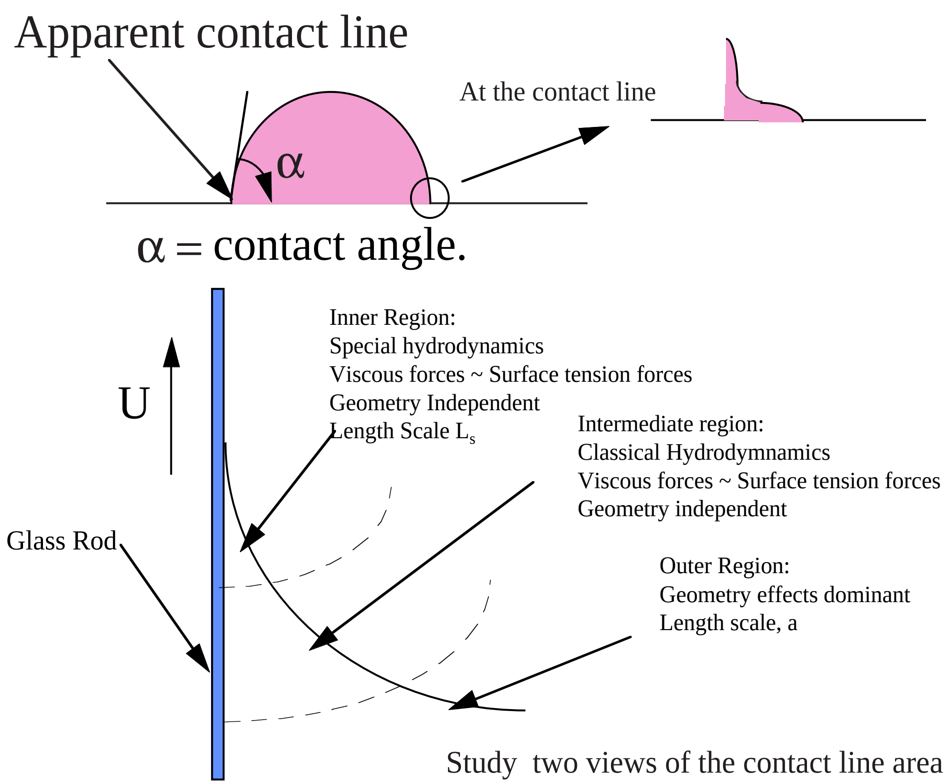
Test Matrix:
- multiple cylindrical test cells (~ 3 geometries)
- various rod velocities
- at least 2 fluids (1 low and 1 high viscosity)
- about 250 tests at 20 minutes/test

Data Reduction: real-time image processing

Special Considerations:
- concentric surfaces (rod in cylinder) must remain parallel
- on-orbit fill may be required
- very small tracer particles (1 to 5 micron) proposed

Facing figure shows different thin film regions and dynamic contact angle.

CONTACT LINE HYDRODYNAMICS (f2)



Study two views of the contact line area for various velocities, fluids, and container dimensions.

A.2.3 RHEOLOGY OF NON-NEWTONIAN FLUIDS (f3)

Key Words: extensional viscosity, uniaxial stretching, dilute polymers, stress response, constant strain rate deformations.

Goals of Experiment:

- characterize extensional viscosity in uniaxial flow for dilute polymer solutions
- characterize internal fluid flows (samples seeded with glass spheres)
- generate homogenous shear free flow while measuring stress response during constant strain rate deformation

Principal Measurements/Observations:

- force exerted by fluid; 1-10000 ± 1 and 100-10^6 ± 100.
- optical imaging: illuminate the center plane of the fluid column and record the experiment using a high resolution, high speed video camera. Desired frame rate = 30 to 100 fps; 5 to 10 cm field of view
- fluid column velocities: range 0.2 to 150 cm/s ± 0.01 cm/s, control set point velocity to within ± 0.01 cm/sec
- fluid column radius: radius reduces as column stretches; measure radius; initial radius = 1.7 cm.
- fluid column length: initially 0.3 cm, stretching to about 45 cm.
- molecular stress: birefringence technique, single point measurements.

Sample Materials:

- fluid column: "Boger Fluid" comprised of HMW polystyrene in LMW polystyrene solution
- bulk fluid: air
- 50 micron diameter silver coated glass spheres as seed particles

Test Environment:

- Acceleration:
  - quasi-static: < about 0.02 g
  - vibratory: < 0.02 g for frequencies < 5 Hz
- Thermal:
  - ambient conditions (5 - 25°C) stabilized to ±0.1 C during measurement
- temperature : nominal fluid column temperature: 20 to 25°C controlled to ± 0.2°C

Test Matrix:

- Henky strain attained by fluid sample e >5
- constant strain rate test will define stretching velocities
- two test fluids
- range of test times required per test: 1-180 secs.
- about 20 tests at 60 minutes/test.

Data Reduction:

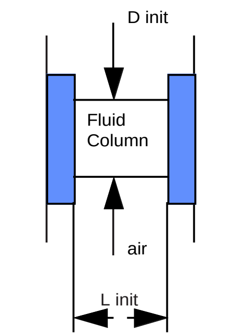
- Convert force, radius and velocity measurements to extensional viscosity

Special Considerations:

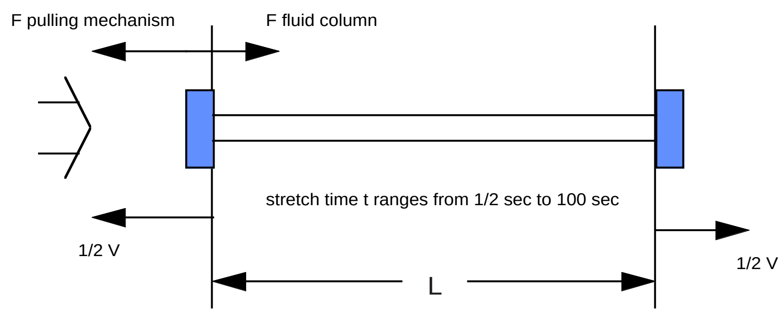
- equal stretching of fluid column from each end
- end plate diameter reduction as a function of stretch distance (to reduce end effects on column)

Facing figure shows measurement of one of the rheological properties of interest -- extensional viscosity.

RHEOLOGY OF NON-NEWTONIAN FLUIDS (f3)



initial condition for fluid column



final condition for fluid column after stretching occurs

$$L = L_{\text{initial}} * e^{(\text{strain rate} * t)}$$

theoretical relationship of final stretch length L, initial length L initial, strain rate, and time t

A.2.4 HARD SPHERE COLLOID PHYSICS (f4) and

A.2.5 COLLOID PHYSICS (f5)

Key Words: light scattering, volume fraction, phase transition, crystallization, rheology

Goals of Experiment:

- characterize kinetics of nucleation and growth of crystalline or glassy phase
- quantify at what volume fractions dispersions undergo phase transitions.

Principal Measurements/Observations:

- static and dynamic light scattering (Bragg scattering)
- imaging of colloidal samples with ~ 1 to 5 micron particles in test cell (10 x 20 mm field of view resolved to 50 micron); 0.1 to 2 frame/sec
- rheological measurements such as for viscosity and elasticity

Sample Materials: polymethylmethacrylate spheres suspended in a refractive index matched hydrocarbon mixture (decalin and tetralin); silica and gold particles for fractal aggregates, and PMMA-metal combinations for binary studies

Test Environment:

- Acceleration
  - quasi-static: <1 milli g
  - vibratory: data not available
- Thermal:
  - ambient (20 - 25°C) stabilized to ± .5°C

Test Matrix:

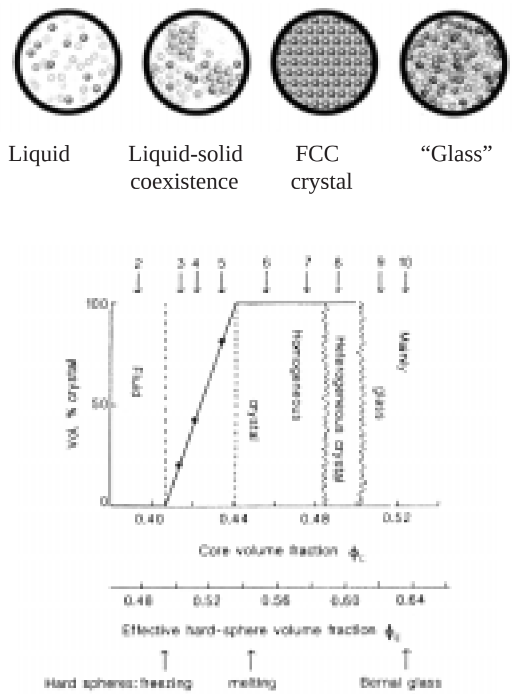
- multiple concentrations of polymethylmethacrylate spheres (0.45 to 0.65 volume fraction)
- decalin and tetralin mixtures for host liquid
- about 25 to 100 tests at 24 hours/test on the average.

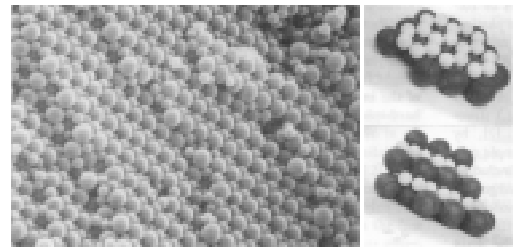
Data Reduction:

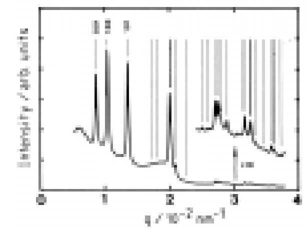
- color images before and after crystallization
- correlograms recorded and indexed to time, duration, position, laser source, temperature, laser power, frequency/amplitude of angular rotation.
- video of sample during melt

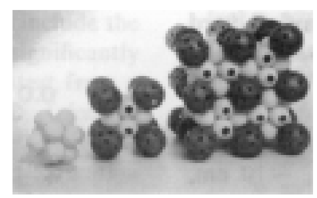
Facing figure shows various colloidal dispersion states for different volume fractions.

HARD SPHERE COLLOID PHYSICS (f4) LLOID PHYSICS (f5) and CO









A.2.6 STUDIES IN ELECTROHYDRODYNAMICS (f6)

Key Words: electric fields, stability of fluid cylinders

Goals of Experiment:
- study stabilizing effects of electric fields on fluid columns
- characterize length/diameter ratios which can be sustained in presence of fields

Principal Measurements/Observations:
- longitudinal electrical field up to 20 kV (AC fields in range 0 to 5 kV/cm ± 5% and at 0 to 500 Hz)
- video images of the fluid column (diameter to within 1% over range 3 to 5 mm); two views required
- flow velocity within transparent fluid column (velocity range to 1 cm/sec within 5 %)

Sample Materials: sample is a "column" fluid (silicone oil or castor oil) residing within a "host" fluid (air, SF_6, silicone oil, or castor oil)

Test Environment:
- Acceleration:
  - quasi-static: < 10 micro-g
  - vibratory: no requirements stated.
- Thermal:
  - ambient conditions stabilized to ± 0.5 C° during each sample run

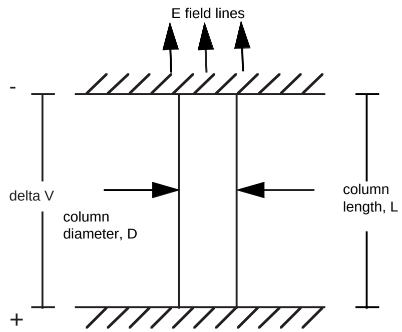
Test Matrix:
- multiple (up to ~ 80) tests at ~ 30 minutes/test using length/diameter ratios (0 to 10), and multiple fluid combinations
- varying electric field strengths and frequencies

Data Reduction:
- real-time imaging and processing (edge detection)
- Fast Fourier Transform calculations of the edge.

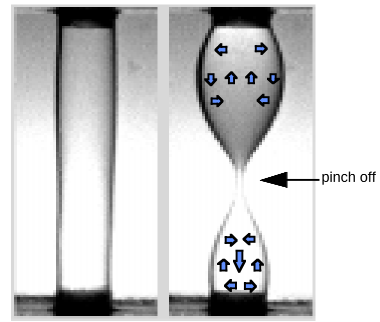
Special Considerations:
- column deployment using large electric fields can cause electric arcs.
- controlled decrease of field strength while monitoring column diameter (observe pinch-off at each length/diameter)
- velocity measurements and high frame rate video desired around pinch-off conditions.

Facing figure shows liquid column and its shapes under varying electric fields.

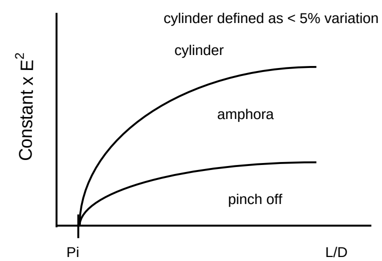
STUDIES IN ELECTROHYDRODYNAMICS (f6)



physical layout of test region

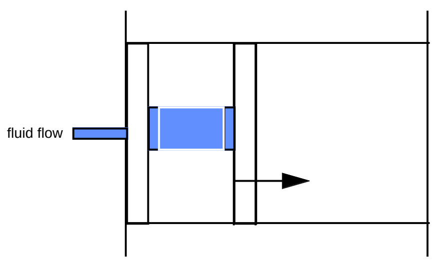


pinch off phenomena caused by reducing electrical field for L/D s greater than π ανδ φλοω πηενομενα ιν λιθυιδ χολυμν υνδερ στυδψ (ϖελοχιτψ)



relationship between electric field and L/D to be determined by experiment test points

Science Phenomena



deployment of fluid column by moving right boundary as fluid is injected in to test area

Operational Considerations

A.2.7 NUCLEATION AND GROWTH OF MICROPOROUS CRYSTALS (f7)

Key Words: crystal growth, microporous ceramic, catalyst, biomineralization

Goals of Experiment:
- measure/observe crystal growth of zincophosphate

Principal Measurements/Observations:
- measure particle sizes ranging from 1 nm to 3 mm
- measure particle size (range 100 to 6000 Angstroms) during growth using laser light scattering/visual imaging
- image solution (field of view 1 to 10 cm with resolution of 10 micron)
- use laser light scattering for resolution below 5 microns.

Sample Materials: zinc and phosphate micelles in hexane

Test Environment:
- Acceleration:
  - quasi-static: < 0.1 milli-g
  - vibratory: no requirement stated
- Thermal:
  - from 20 to 25 ± 1.0°C during test

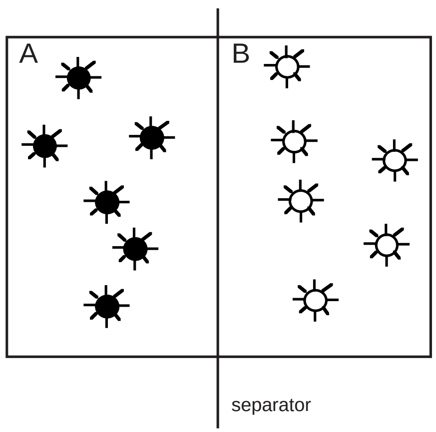
Test Matrix:
- multiple runs (15 to 20 samples) using different concentrations, and temperatures
- all measurements completed in 10 days

Data Reduction:
- correlograms recorded and indexed.
- real-time video

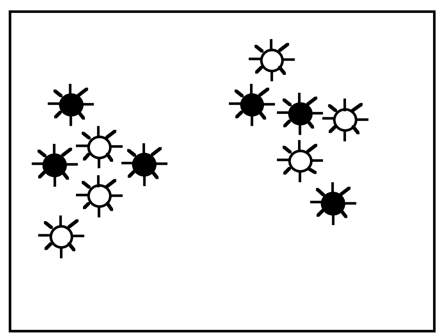
Special Considerations:
- samples must be mixed on-orbit within 10 days of preparation.
- samples must be returned to PI within a "few weeks"

Facing figure shows mixing of substances A and B, and subsequent crystal growth.

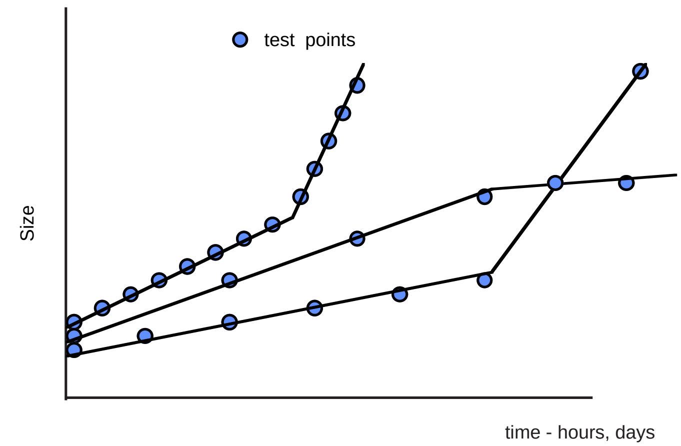
NUCLEATION AND GROWTH OF MICROPOROUS CRYSTALS (f7)



initial test condition with substances A and B separated



crystals form over time: anticipated formation time 1 hours - 10 days



growth of crystals as a function of time, size measured periodically during growth

Zinc micelles

Phosphate Micelles

A.2.8 INTERACTIONS OF BUBBLES AND DROPS IN A TEMPERATURE GRADIENT (f8)

Key Words: bubbles, drops, temperature gradient, surface tension

Goals of Experiment:

- observe characteristics of bubbles and drops (shape, point velocities, field velocities) within a host fluid and a known temperature gradient
- characterize mechanisms for drop/bubble movement

Principal Measurements/Observations:

- measure temperature gradient (extreme from -20 to 50°C for "low" gradient and 50 to 120°C for "high" gradient); variation in gradient direction: ± 1.0°C/mm, and variation transverse to gradient, ± 0.1°C
- measure drop/bubble velocity (over range 0.01 to 1.0 cm/sec to within < 5%)
- measure drop/bubble size: dia. 1 to 20 mm, +/- 1 %
- measure velocity field around the drop/bubble; within 1 drop dia. in all directions except "downstream" (2 dia.)
- measure temperature field around drop/bubble
- characterize drop/bubble shape.
- characterize motion of drop/bubble due to laser heating
-

Sample Materials:

- host fluid typically silicone oil
- bubbles typically air
- drops are typically Fluorinert (FC-70, FC-75)

Test Environment:

- Acceleration:
  – quasi-static: 1 to 10 micro-g
  – vibratory: sensitivites for freq's < 0.01 Hz
- Thermal:
  – stable gradients established prior to injections
- – Cell dimensions, > 7 bubble dia. wide, and 10 cm long.

Test Matrix:

- multiple runs using different temperature gradients, drop/bubble sizes, numbers of drops/bubbles
- 1 to 15 minutes/test, and 1 to 2 hours for gradient equilibration.
-

Data Reduction:

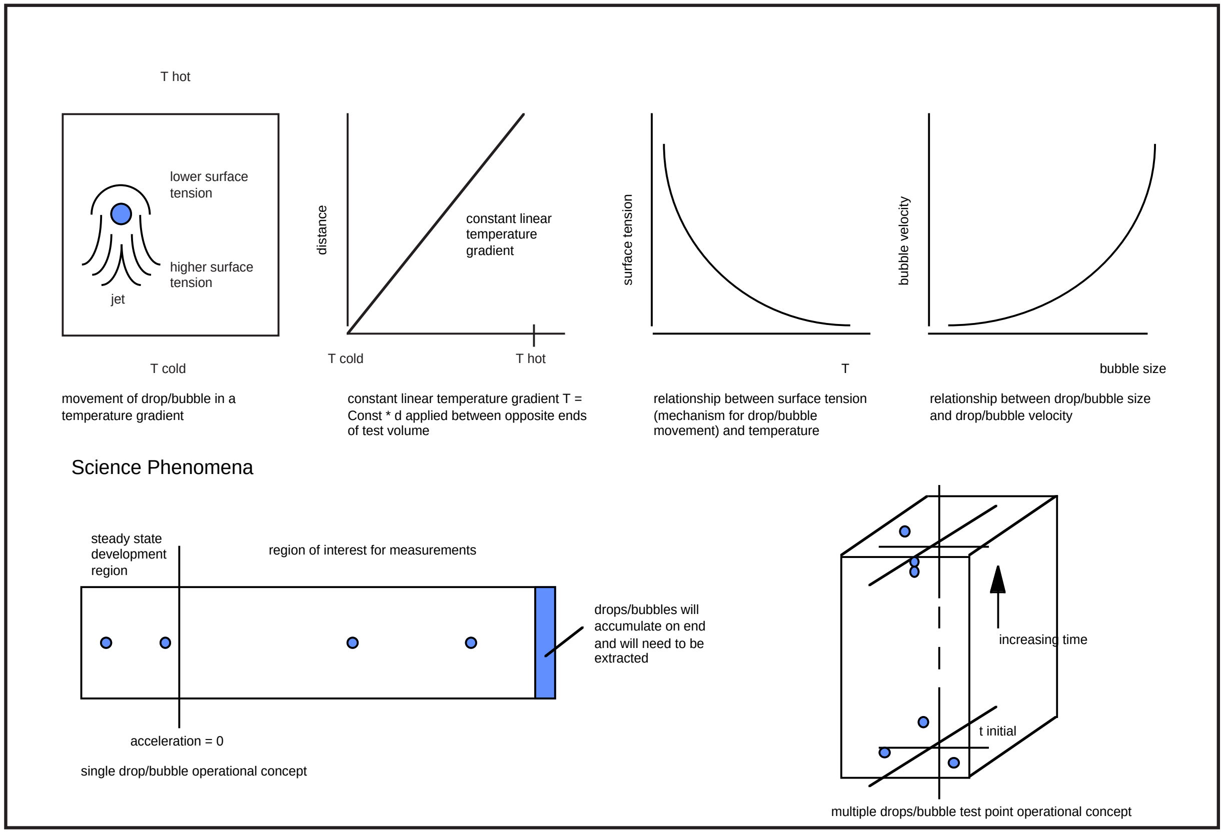
- real-time imaging required

Special Considerations:

- drops/bubbles are deployed at special initial conditions (locations and velocities)
- temp. and vel. fields measured when drops/bubbles are within 1 to 2 diameters of another drop/bubble
- single drops/bubbles deployed at near 0 velocity and monitored through acceleration to steady state velocity
- temperature gradient must be steady before deployment

Facing figure shows thermocapillary migration of bubbles.

INTERACTIONS OF BUBBLES AND DROPS IN A TEMPERATURE GRADIENT (f8)



A.2.9 THERMOCAPILLARY MOTION OF BUBBLES AND DROPS - POPULATION OF BUBBLES (f9)

Key Words: bubbles, drops, temperature gradient, thermocapillary motion, coalescence

Goals of Experiment:
- characterize times for disperse drops/bubbles to coalesce in a temperature gradient (thermocapillary motion)
- observe mechanism of drop/bubble coalescence near the liquid interface

Principal Measurements/Observations:
- measure rate of phase separation (by measuring the liquid-vapor interface position.
- measure drop diameter over range of 50 microns - 10 mm, to a precision of 1 to 5% of diameter.
- image drop coalescence mechanism near fluid-fluid interface

Sample Materials:
- non-mixing fluids at 1 to 10% by volume
- castor oil/ silicon oil; ethanol-diethylene glycol/silicon oil; water/butyl benzoate

Test Environment:
- Acceleration:
  - quasi-static: < 1 milli-g
  - vibratory: < 1 milli-g for frequencies < 1 Hz
  - vector alignment desired
- Thermal:
  - stable gradients established per measurement requirement of basis experiment. f8
- Test cell dimensions ~ 15 x 1 x 1 cm
- initial drops (2 to 50 micron) "completely" dispersed in host fluid

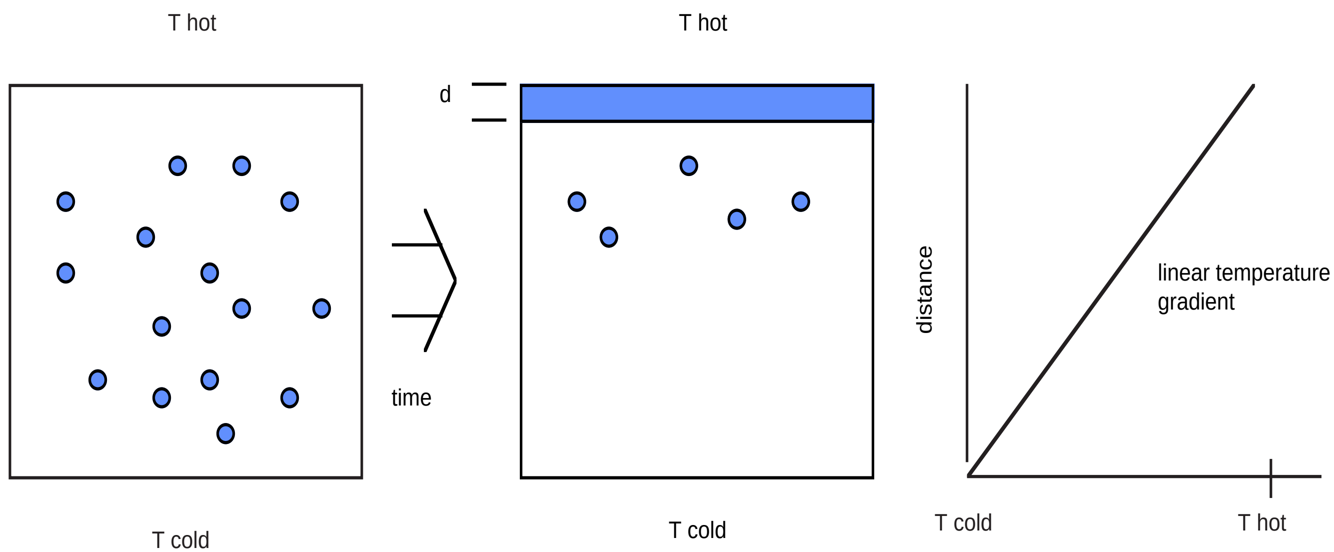
Test Matrix:
- multiple runs using different temperature gradients
- multiple runs using different fluids and drops concentrations
- multiple runs using different cell lengths
- take measurements at 15 to 20 intervals during the test time.
- about 75 tests at 1 to 5 hours/test

Data Reduction:
- None

Special Considerations:
- temperature gradient must be developed quickly after droplets are dispersed.
- g-level direction and magnitude must be known – its value and direction is a direct input driving the physics of the experiment

Facing figure shows thermocapillary migration and coalescence of a population of fluid drops.

THERMOCAPILLARY MOTION OF BUBBLES AND DROPS - POPULATION OF BUBBLES (f9)



drops evenly dispersed in non mixing host fluid

as time progresses, drops combine at hot end of test region, the distance d defines the phase separation between drops and region of coalescence

linear temperature gradient T = Const * d applied between opposite ends of test volume

A.2.10 INTERFACIAL TRANSPORT AND MICELLAR SOLUBILIZATION PROCESSES (f10)

Key Words: interfacial transport, diffusion

Goals of Experiment:
- Characterize diffusion rates of solutes, surfactants, micelles through a liquid-liquid interface

Principal Measurements/Observations:
- non-intrusive concentration measurement using interferrometry or a fluorescence recovery method.
- high speed video (300 fps for 5 seconds).
- monitor micellar motion using laser light sheet and 1 to 5 micron seed particles.
- video microscopy; 250 x 500 micron field of view resolved to 1-5 micron for interferrometry
- field of view: 0.25 mm x 0.5 mm, and 0.25 x 40 mm, resolved to 25 microns for optical viewing
- single shot images 5 minutes between frames for B/W; 15 minutes between frames for color.

Sample Materials:
- organic liquids: ethanol, heptane, and toluene
- industrial surfactants (AOT, SDS or similar), and water.
- industrial solutes such as methylnicotinate.

Test Environment:
- Acceleration:
  - quasi-static: < 0.1 to 1.0 milli g
  - vibratory: no requirement stated
- Thermal:
  - range 10 to 35°C controlled to ± 0.01°C

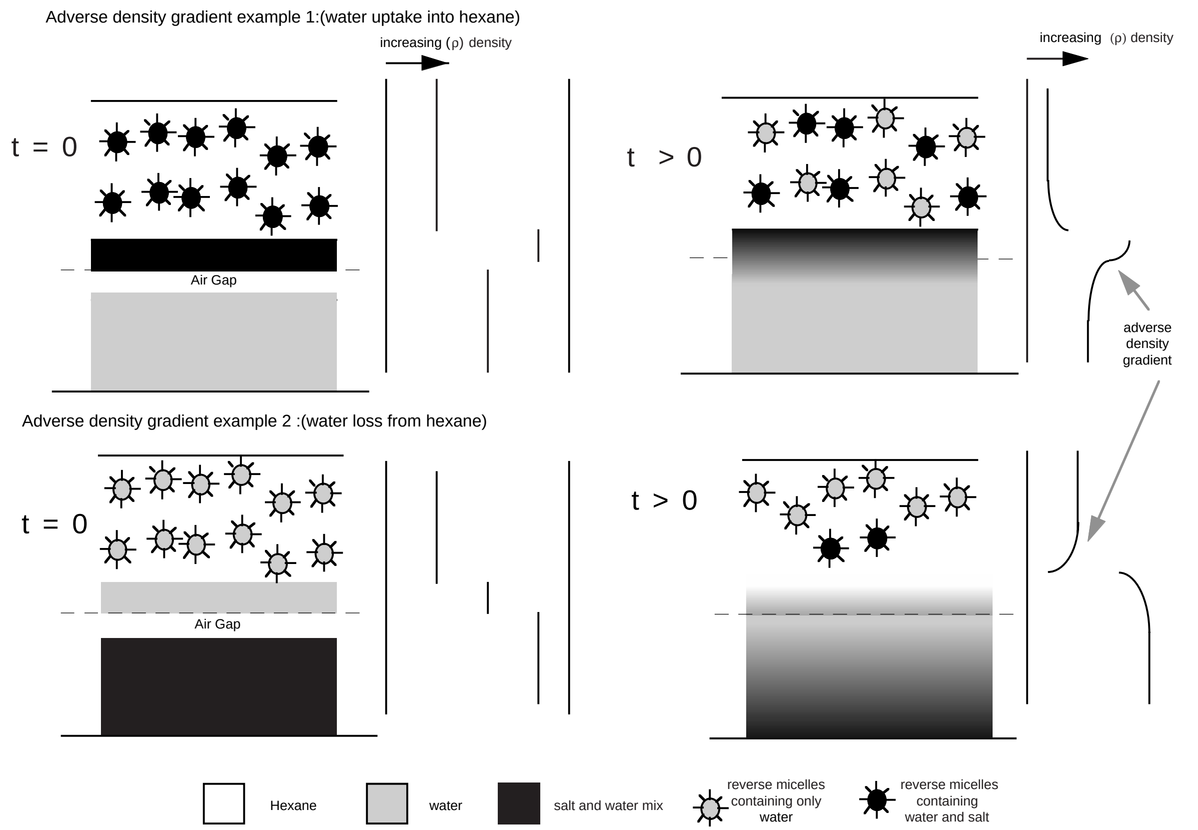
Test Matrix:
- multiple runs (50 to 100) at 1 to 2 hours per run.
- different temperatures, chemical combinations, and concentration profiles

Data Reduction:
- image showing gradients of (fluorescence) light intensities.

Special Considerations:
- flammable fluids
- system very sensitive to thermal excursions.

Facing figure shows interfacial transport and micellar solubilization process.

INTERFACIAL TRANSPORT AND MICELLAR SOLUBILIZATION PROCESSES (f10)



A.2.11 THERMOCAPILLARY AND DOUBLE-DIFFUSIVE PHENOMENA (f11)

Key Words: temperature gradient, concentration gradient, convection, instability, surface tension gradient, thermocapillarity, diffusocapillarity

Description: Three types of experiments: convection, instability, and double diffusion. These differ in that the direction of the temperature gradient is either parallel to the free surface (convection); or orthogonal (instability); or there is no free surface at all (double diffusion).

Goals of Experiment:

- Characterize fluid dynamics transitions to turbulence, interaction of thermocapillarity and diffusocapillarity that are driven by surface tension or density gradients
- study of Marangoni-Benard instabilities (onset, post-onset convection, effect of diffusocapillarity on onset)

Principal Measurements/Observations:

- measurement of fluid temp., ranging, 0 to 100°C, with walls interfacial temperatures accurately measured
- flow imaging (two orthogonal views)
  - particle (~70 micron) imaging velocimetry (velocity range 0 - 20 cm/sec resolved to ±1%)
  - infrared imaging of surfaces
  - shadowgraphy of local density-driven flows

Sample Materials:

- silicone oils are typical; glycerol and salt solutions have been employed also

Test Environment:

- Acceleration:
  - Instability Experiments:
    - quasi-static: < 1 milli g (with vector alignment); < 1 micro-g (with no alignment)
    - vibratory: no requirement stated
    - vector alignment: orthogonal to free surface ±1°
  - Convection Experiments:
    - quasi-static: < 0.1 milli g
- Thermal:
  - range 0 to 100°C for normal fluids

– Rectangular and circular test cells with aspect ratios from 0.1 to 10 will be studied

Test Matrix:

- multiple temperature differences from 0 to 100°C
- multiple concentration gradients
- selected aspect ratios as indicated above
- about 150 tests at 1-2 hours/test.

Data Reduction:

- real-time video

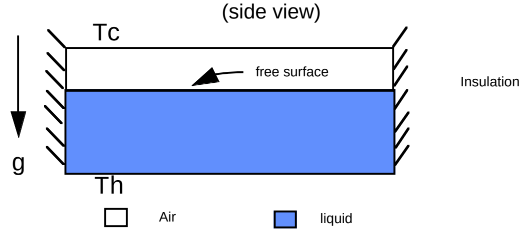
Special Considerations:

- fluid handling (fill chambers)
- propose "schlieren" for IR view
- gravity alignment may be req'd for double diffusion

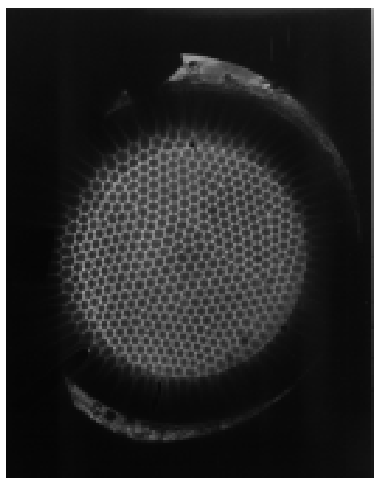
Facing figure shows various thermocapillary and double diffusive phenomena.

THERMOCAPILLARY AND DOUBLE-DIFFUSIVE PHENOMENA (f11)

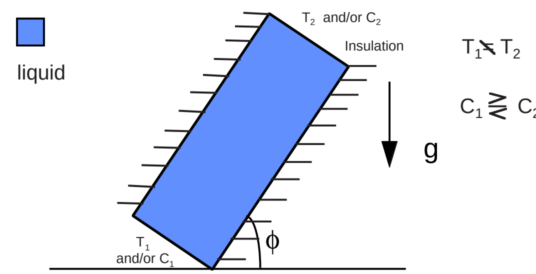
(i) Thermocapillary Instability Experiment configuration
(side view)



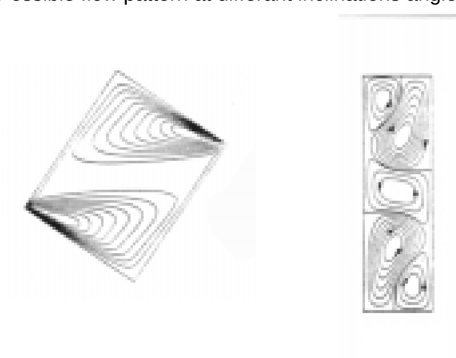
(ii) Flow Pattern from the onset of thermocapillary instability
(top view)



(iii) Double Diffusive Experiment Configuration



(iv) Possible flow pattern at differant inclinations angles



a) $\theta = 40^o$ b) $\theta = 90^o$

A.2.12 CRITICAL POINT PHENOMENA (f12)

Key Words: phase transition, critical point, fluctuations

Goals of Experiment:

- Characterize fluid dynamics very near the critical temperature of pure fluids and mixtures

Principal Measurements/Observations:

- sub-milli-Kelvin thermometry required to prepare samples to thermodynamic realms of interest
- measurement techniques employed to date (non-intrusive techniques are of primary interest):
  - dynamic light scattering of density fluctuations
  - interferometry of density gradients
  - moderate to high resolution imaging of phase change
  - low-shear viscometry
  - precision measurements of electric potential, current, and temperature.
  - precision calorimetry

Sample Materials:

- pure fluids (e.g., SF_6, Xe, H_2O, CO_2)
- mixtures (methanol/cyclohexane)

Test Environment:

- Acceleration:
  - quasi-static: < 0.01 milli g (unless better control of thermal gradients can be attained)
  - vibratory: spikes up to 1 milli-g can be tolerated for short periods of time
- Thermal:
  - fluids temperature range from about 15 to 375°C (depending on fluid); steady ambient temperatures (±0.5°C) desired.
- Precision thermostat is a prerequisite (resolution and set-point control to < 10 micro-Kelvin is required)
- Precision sample preparation required (prepared to critical density or concentration and sealed) to permit access to critical point

Test Matrix:

- typical approaches:
  - very slow scan (rates as slow as 50 to 100 micro-K/hr) through the critical point
  - multiple isothermal set points relative to the critical temperature
- experiments may employ electric, accoustic fields, local heaters, physical stir mechanisms, and mechanical viscometers for these experiments

Data Reduction:

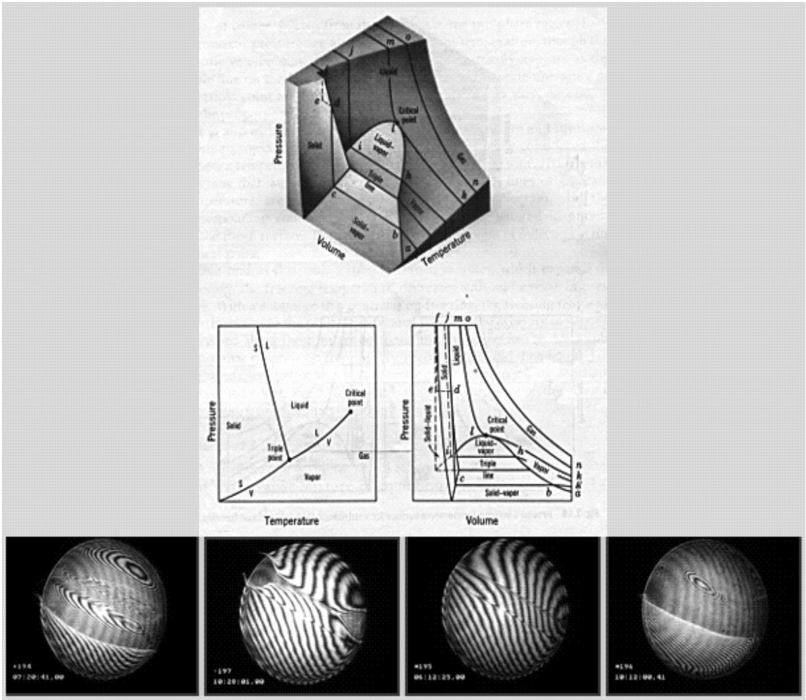
- dependent upon diagnostic technique employed

Special Considerations:

- precision, low-noise electronics required for such measurements

Facing figure shows the critical point in a generic p-v-T surface, and typical interferograms of near critical SF_6.

CRITICAL POINT PHENOMENA (f12)



Typical interferograms of near critical SF6, showing the vapor, liquid, or supercritical fluid regions.

A.2.13 MULTI-PHASE FLOW AND BOILING (f13a and b)

Key Words: flow regimes, pressure drop, void fraction, interfacial friction, surface waves, boiling, and bubble nucleation.

Goals of Experiment:
- two kinds of experiments: multiphase flow (a) and boiling (b)
- characterize flow regimes, pressure drops, void fractions, and heat transfer in two-phase flow in straight cylinders and in tubes with fittings (a); characterize bubble nucleation, growth, and departure (b)
- characterize bubble velocities and distributions, wave structures in flow (a) or around bubble (b)
- characterize various flow boiling regimes (a)

Principal Measurements/Observations:
- imaging of flow and phase separation (two orthogonal views, front and rear views) (a); bubble growth (b)
- frame rate imaging, up to 1000 fps (a), ~ 10 fps (b)
- measure heat transfer rate (rates to 100 $Watt/cm^2$)
- measure local and global void fraction (a)
- measure local flow velocities (gas flow from 0.05 to 10 m/sec; liquid flow from 0.05 to 2 m/sec) (a)
- measure bubble growth and external temp. fields, (b)

Sample Materials:
- liquids: water, water-glycerin, water-surfactant, ammonia, and fluorinerts (a); PF5060, water (b)
- gasses: air, argon, xenon (a)

Test Environment:
- Acceleration:
  - quasi-static: < 10 (a) and < 20 (b) micro-g
  - vibratory: avoid vibrations less than 10 Hz.
- Thermal:
  - fluid temperature range –15 to 100+°C, 1 to 10 atm. pressure; precision ±0.1°C, controlled to +/- 0.5 deg-C (a)
  - temperature ranges from about 60 to 100 deg-C (b)

– **Test Matrix**:
- multiple flow rates with independent control of gas and fluid velocities, multiple line diameters and cross-sections, and various subcooling and heat-flux levels (a)
- multiple press., super heats, fluids, and heat fluxes (b)

Data Reduction:
- video image processing is desired to trigger and achieve very high frame rates.

Special Considerations:
- relatively long straight runs where L/D > 100, and larger volumes of fluid typically required; may need special power batteries and chiller units.

Facing figure shows how gravity levels strongly affect two-phase flow and boiling phenomena.

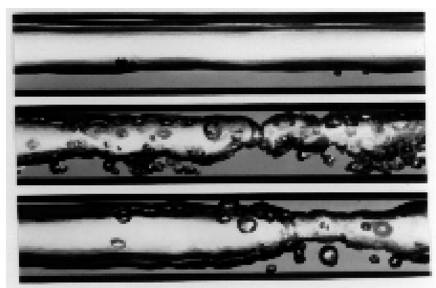
MULTI-PHASE FLOW AND BOILING (f13)

Effect of G-Level on Multiphase Flow

Stratified Flow
Normal Gravity
~ 1.0 g

Stratified Wavy Flow
Lunar gravity
~ 0.17 g

Slug-Annular Flow
Microgravity
<0.01 g



Gas

Liquid

Flow →

Air-Water in 1.27 cm ID Tubes
Superficial Gas Velocity ~ 2.1 m/s
Superficial Liquid Velocity ~ 0.07 m/s

Comparison of Normal- and Low-gravity Pool Boiling from the Lewis Zero Gravity Facility 11/28/89

Fluid: Freon-113 Side View	**Fluid: Freon-113 Side View**
Normal Gravity (1.0 g)	Low-gravity (10^{-6} g)
Pressure = 22.5 psia	Pressure = 16 psia
Temp (sat) = 142° F	Temp (sat) = 122 ° F
Heat Flux = 8 W/cm^2	Heat Flux = 8 W/cm^2
Subcooling = 5 ° F	Subcooling = 5 ° F

Gravity Level Strongly affects the nature of boiling

A.2.14 MECHANICS OF GRANULAR MEDIA (f14)

Key Words: shear cell, separation, glass transition, mechanics/dynamics of granular media, avalanche, debris slide, sediment transport, granular flow in risers.

Goals of Experiment:
- characterize collisions among binary mixtures of particles and textured walls
- characterize segregation/distribution (scale and direction) of particles
-

Principal Measurements/Observations:
- imaging of flow up to 60 cm/sec; 20 to 40 cm field of view
- high frame rate imaging, up to 500 fps estimated
- measure capacitance across flow (to determine average distribution of particles)
- measure frequency and intensity of particles on shear wall

Sample Materials:
- spheres of various sizes, types (steel and carbide tungston), diameter ratios, and volume fractions among the various test cells

Test Environment:
- Acceleration:
  - quasi-static: < 2 milli-g
  - vibratory: no requirement stated (none likely)
  - vector alignment: no requirement stated
- Thermal:
  - ambient (~25°C) ±3°C

Test Matrix:
- multiple tests (to about 20); different shear rates (velocities), sphere sizes, sphere diameter ratios, sphere materials, and volume fractions

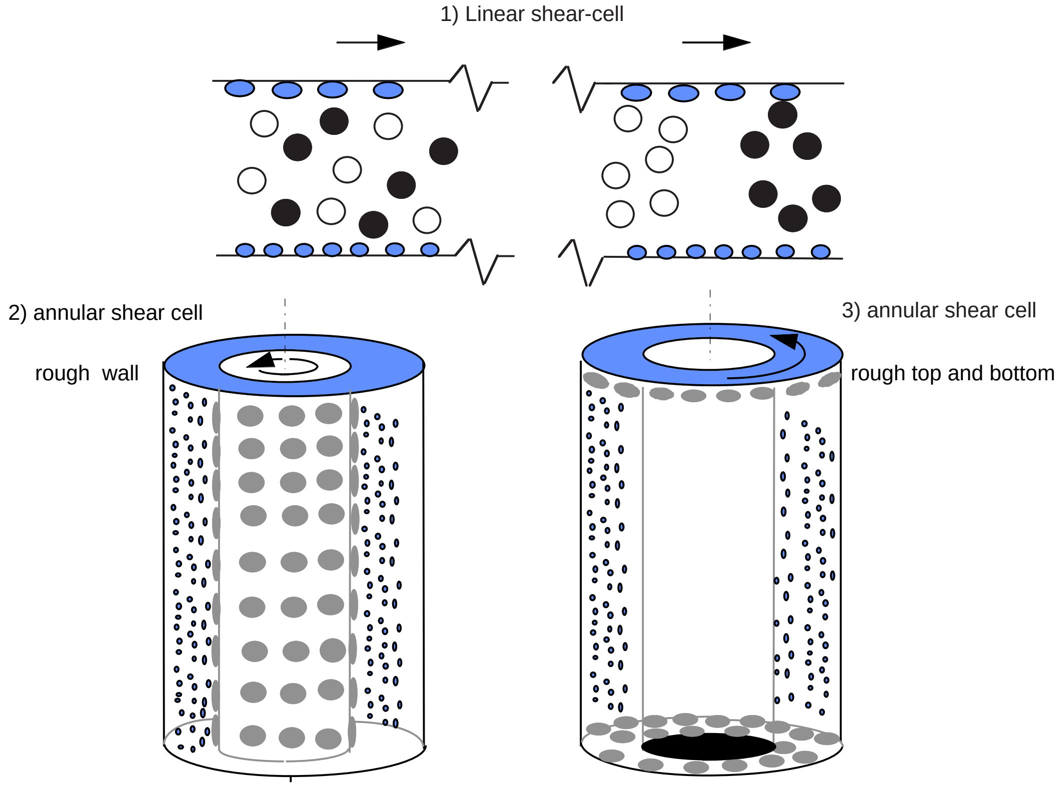
Data Reduction:
- None

Special Considerations:
- Apparatus may cause vibrations.

Facing figure shows various geometries and boundary types used to study the various phenomena such as segregation, and radial particle distribution of granular media.

MECHANICS OF GRANULAR MEDIA (f14)

Sand, Glass, Steel or Coal particles in



A.2.15 SHEAR RHEOLOGY OF COMPLEX FLUIDS (f15)

Key Words: light scattering, volume fraction, bubbly suspensions, rheology, video microscopy, and uniform shear

Goals of Experiments:

- characterize the physics of the discontinuous phase; e.g., bubbly suspensions (high liquid content) as well as foams (low liquid content) in constant shear environments; also particulate suspensions
- determine elastic characteristics of foams as well as bubble distributions in a suspension
- quantify at what volume fractions suspensions lose their elastic properties

Principal Measurements/Observations:

- general & microscopic for imaging bubbles/foam near walls
- diffusive transmitted spectroscopy and diffusive wave spectroscopy (DTS & DWS); long coherence length laser
- measure shear strain and shear strain rates, and localized volume fractions
- imaging with a field of view of about 10 bubble diameters where the diameters range from 10 to 500 microns for the foam cases; and 2 to 3 mm for suspensions
- required frame rates from 30 to 1000 fps

Sample Materials:

- foam experiments use aqueous solutions of sodium-AOS-and either butanol, dodeconol or polyacrylic acid
- suspension experiments use aqueous salt solutions with no surfactants

Test Environment:

- Acceleration
  - quasi-static: < 30 micro-g (suspensions) and < 0.01 g for foams
  - vibratory: data not available
- Thermal:
  - ambient (20 - 30°C) and controlled to ± .2°C for all samples

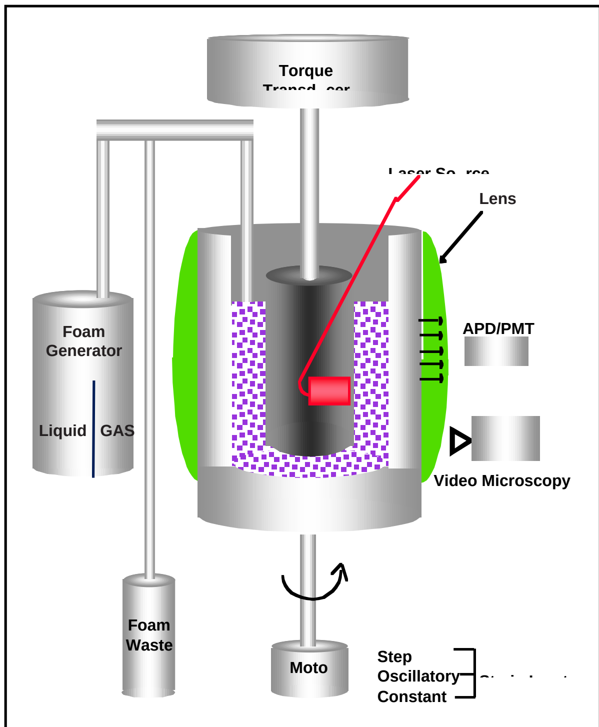
Test Matrix:

- various shear rates, bubble sizes/diameters, bubble volume fractions, and fluid combinations
- about 30 to 50 tests
- ranging from 30 minutes per test almost 1 day

Data Reduction:

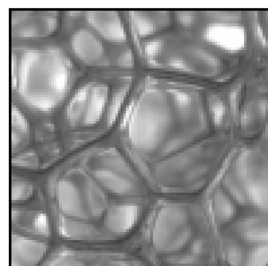
- correlograms recorded and indexed to time, duration, position, laser source, temperature, and laser power
- videos of samples prior to and during shear
- determination of global and local volume fractions of suspensions and foams

Shear Rheology of Complex Fluids (f15)

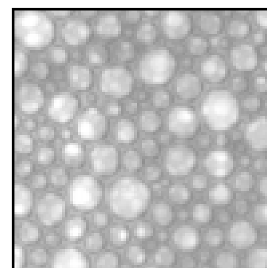


Description: Foam is generated within a couette cell, and video microscopy and diffusing wave spectroscopy (DWS) data measurements are initiated as the foam coarsens (bubbles grow bigger). Rheometry is performed at various strain rates while torque, pressure, and additional DWS measurements are made.

Approx. 50 tests are required, with water content varied from 5% to 40% and up to 4 surfactant solutions investigated..



Dry Foam



Wet Foam

Objective: Simultaneous light scattering and rheological measurements are made in microgravity as a function of liquid content and bubble size (30-300 microns) to determine the nature of foam rheology and stability in terms of underlying bubble-scale structure and dynamics of the material.

A 2.16 MESOCOPIC STUDIES OF COLLOIDS AND COMPLEX FLUIDS (f16)

Key Words: light scattering, volume fraction, phase transition, crystallization, rheology, video microscopy

Goals of Experiments:

- characterize kinetics of nucleation and growth of coarsening crystal structures, as well as determining rheological morphological properties
- quantify at what volume fractions dispersions undergo phase transitions (emphasizing low & high vol. fractions) – i.e. phase diagram
- study not only hard spheres, but also polymer mixtures, and fractal aggregates
- actively manipulate particles to perform micro-rheology and effects of pattern perturbation

Principal Measurements/Observations:

- static and dynamic light scattering, and spectrophotometry
- laser tweezers for particle manipulation
- video microscopy including DIC, phase contrast & light and dark field imaging, and fluorescence
- imaging of ~ 1 to 5 micron particles in test cell (10 x 20 mm field of view resolved to 50 micron); 0.1 to 2 frame/sec

Sample Materials:

- polymethylmethacrylate (PMMA) spheres suspended in a refractive index matched hydrocarbon mixture of decalin & tetralin; particles 10 nm to 5 microns in size
- also polystyrene, silica, and zinc sulphide particles for fractal aggregates

Test Environment:

- Acceleration
  - quasi-static: < 0.1 milli-g
  - vibratory: data not available
- Thermal:
  - ambient (20 - 25°C) stabilized to ± .5°C

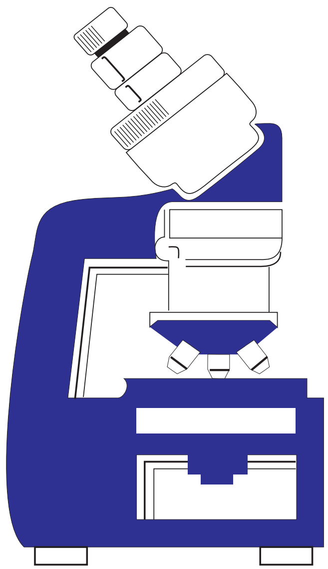
Test Matrix:

- multiple concentrations of PMMA spheres (0.45 to 0.65 volume fraction), various diameters, and diameter ratios
- various template types for introducing perturbations
- decalin and tetralin mixtures for host liquid
- about 500 microscopic test samples (~ 1 to 10 mm in size) at 24 hours/test on the average (all samples periodically diagnosed)

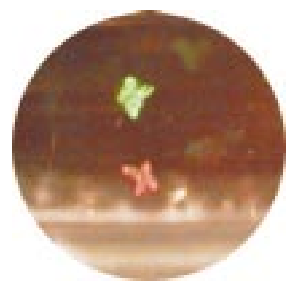
Data Reduction:

- color images before and after crystallization
- correllograms recorded and indexed to time, duration, position, laser source, temperature, and laser power
- video of sample during melt

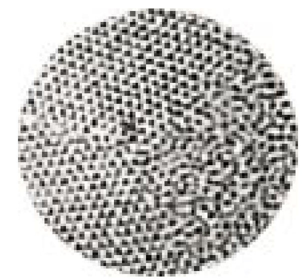
Mesoscopic Studies of Colloids and Complex Fluids (f16)



Description: The colloidal fluid physics of hard spheres. A colloidal modelling system is used to understand the interactions of groups of atoms, of fundamental importance for condensed matter physics, but which are too small to directly examine. Experiments in microgravity on these systems have held pleasant surprises. These include crystals (that were glasses on earth) and dendritic growth.



Colloidal Dendrites



Interface Growth

Objective: Macroscopic and Microscopic Colloidal Studies, structure, nucleation and growth, dynamics and rheology, controlled interface studies, growth from a patterned substrate, and microrheology.

Appendix B - Combustion Basis Experiments

B. COMBUSTION BASIS EXPERIMENTS

B.1 INTRODUCTION

Eleven experiments were selected from the ground or the flight experiment program of the MSAD as examples of the breadth of experimental science currently in the Combustion Program and representative of the types of measurement techniques currently demanded by the investigators. The top-level requirements for implementing these experiments are used primarily in this document to define the "envelopes" of capabilities called out as requirements on the facility.

In Section B2, brief descriptions of these experiments are provided to enable the reader to sense the types of measurements and range of conditions called out for each experiment.

Facing figure displays the titles and numerology of the basis experiments used in this document to develop the requirements envelopes for the combustion facility.

BASIS EXPERIMENTS FOR COMBUSTION

Section#	Exp.#	Experiment Name	Relevant Area
B2.1	c1	Gas-Jet Diffusion Flames	• laminar flames • turbulent combustion
B2.2	c2	Structure of Flame Balls at Low Lewis Numbers	• laminar flames • reaction kinetics
B2.3	c3	Spread Across Liquids	• condensed phase organic fuel combustion • flame spread and fire suppressants
B2.4	c4	Diffusive and Radiative Transport in Fires	• condensed phase organic fuel combustion • flame spread and fire suppressants • laminar flames
B2.5	c5	Smoldering Combustion	• condensed phase organic fuel combustion • flame spread and fire suppressants
B2.6	c6	Droplet Combustion	• droplet and spray combustion • reaction kinetics
B2.7	c7	Laminar Soot Processes	• laminar flames • soot and polycyclic aromatic hydrocarbons
B2.8	c8	Soot Measurement in Droplet Combustion	• droplet and spray combustion • soot and polycyclic aromatic hydrocarbons
B2.9	c9	Unsteady Burning of Contained Reactants	• laminar flames • reaction kinetics
B2.10	c10	Solid Fuels Flammability Boundary	• laminar flames • reaction kinetics • condensed phase organic fuel combustion • flame spread and fire suppressants
B2.11	c11	Radiative Ignition and Transition to Flame Spread	• laminar flames • reaction kinetics • condensed phase organic fuel combustion • flame spread and fire suppressants

B.2

B.2.1 GAS-JET DIFFUSION FLAMES (c1)

Discipline Key Words: combustion, gas-jet, diffusion flames

Goals of Experiment: To study the behavior, structure, and characteristics of gas-jet diffusion flames in microgravity to clarify the role of pressure, oxidizer composition and fuel flow rate on flame development, quasi-steady behavior and extinction.

Principal Measurements/Observations Required:

- Color imaging of flame development to obtain flame height, radius and shape as a function of time
- Temperature field both inside and outside the flame possibly using fine-wire thermocouples or an optical technique
- IR imaging to obtain the local radiative contributions from stable combustion products (e.g., CO_2 at 4.31 microns and H_2O at 1.87 microns)
- Global and local flame radiation, possibly using radiometers, to obtain the radiative heat loss from both the entire flame as well as flame slices
- Intensified imaging of fields of CH (431 nm) and OH (310 nm) radicals to investigate the dim combustion regions near the base and tip of the flames
- Point and field measurements of axial velocity and desirably radial velocity possibly using LDV and PIV

Test Environment: Methane and propane will be burned at flow rates of 3-30 cc/sec at ambient pressures of 0.5-2 atmospheres in 15%-30% oxygen in nitrogen environments.

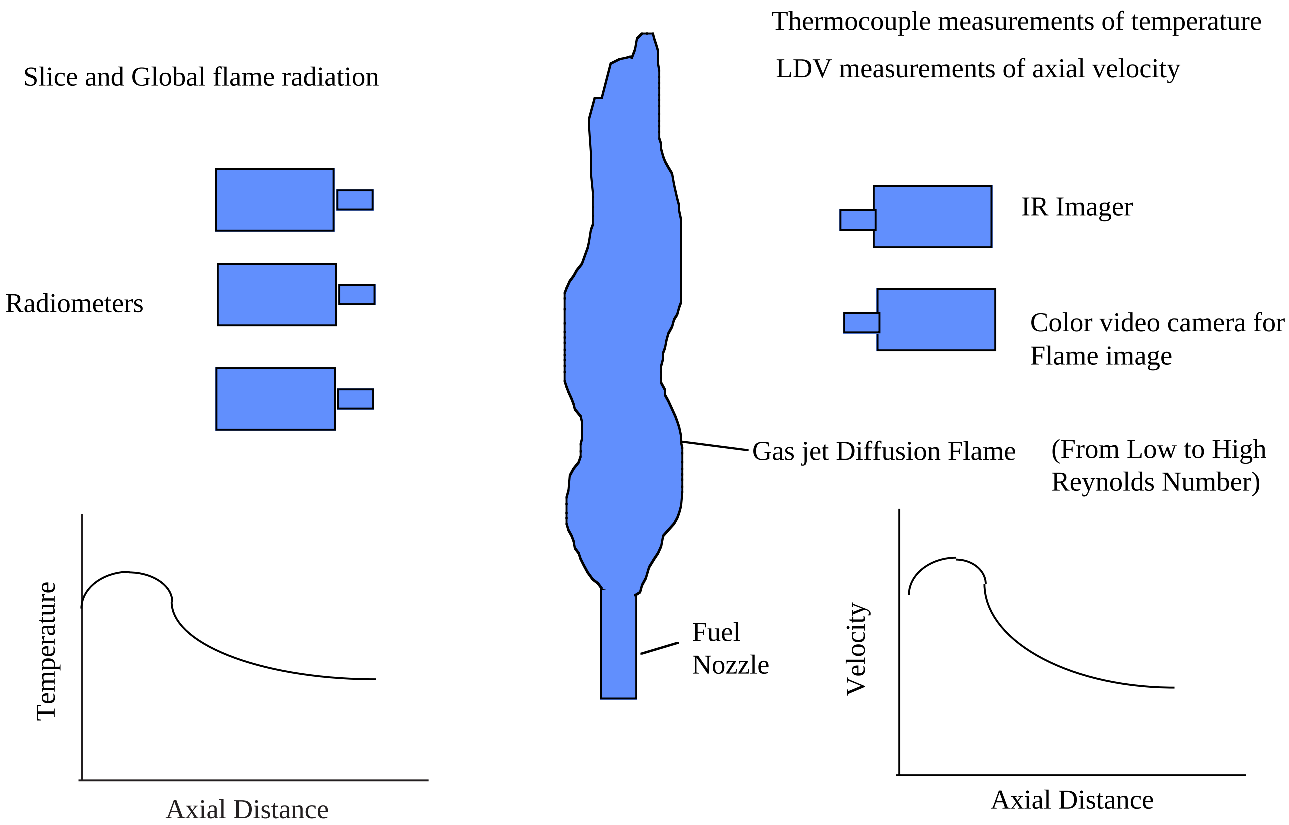
Test Matrix: Approximately 15-20 test points are needed to assess the effects of the environmental variables.

Special Considerations:

- Any intrusive probing must be chosen carefully to minimize disturbances to the flame
- Both radiometers and IR cameras need to be calibrated with a black body source

Facing figure illustrates combustion basis experiment c1.

GAS-JET DIFFUSION FLAMES (c1)



B.2.2 Structure of Flame Balls at Low Lewis Numbers (SOFBALL) (c2)

Discipline Key Words: Combustion, fuels, gases, diagnostics, microgravity

Goals of Experiment: To study the interactions of chemical reaction and heat and mass transfer in the simplest possible configuration for comparison with models of flame stability and propagation limits.

Principal Measurements/Observations Required:

- Imaging provides flame shape, size, duration, and intensity to be compared to modeling predictions.
- Pressure transducer provides the pressure rise and fall during and after combustion.
- Fine wire thermocouples determine the temperature field near the flame balls.
- Radiative emission measurements determine the flame radiation field emitted and adsorbed by the flame balls and gas mixture.
- Gas sampling determines the composition of the reactants and the products, and measures the extent of combustion.
- Acceleration measurements determine the microgravity environment experienced by the flame balls and will determine if any movement is correlated to specific acceleration events.

Test Environment: Premixed gases consisting of fuel, oxidizer, and diluent burn in a constant volume chamber under quiescent, microgravity conditions.

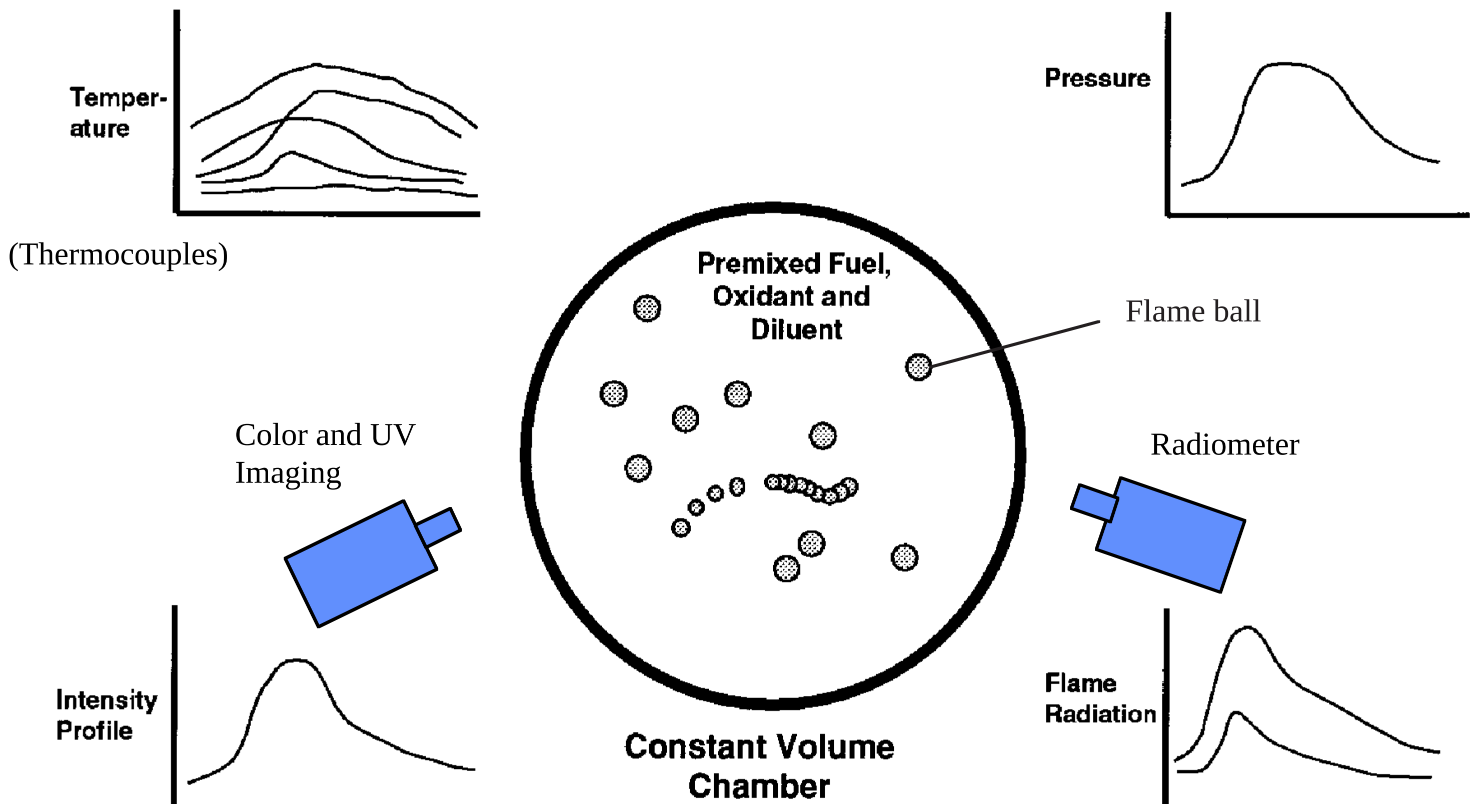
Test Matrix: Fifteen test points will be investigated. The fuel and oxidizer are hydrogen and oxygen, respectively. Diluents are air, carbon dioxide, or sulfur hexafluoride. The initial pressure is 1 or 3 atm. The use of methane as a fuel is under consideration.

Special Considerations:

- Gases are vented to space after combustion. Cleanup of combustion products may be necessary, especially for the sulfur hexafluoride tests.
- Minimum chamber volume is 25 liters. If the chamber is a cylinder, the diameter should be nearly equal to its length.
- An average acceleration level of 4 x 10-4 g0 over the duration of the burn time, up to 100 seconds, is required.

Facing figure illustrates combustion basis experiment c2.

STRUCTURE OF FLAME BALLS AT LOW LEWIS NUMBERS (SOFBALL) (c2)



B.2.3 Flame Spread Across Liquid Pools (c3)

Discipline Key Words: combustion, liquid pools, flame spread, microgravity

Goals of Experiment: To determine the effect of low-speed, forced air flow on flame spread over liquids initially below their flash point (in particular the flame spread rate and character, limiting oxygen index, and effects of pool size/geometry). Measurements of liquid and gas-phase flow and temperature fields will be compared to predictions from a state-of-the-art numerical model.

Principal Measurements/Observations Required:
Initial Set:

- Flame imaging of both the top and side views of the entire tray length.
- Rainbow schlieren deflectometry of both the gas and liquid phases perpendicular to the tray axis to determine temperature gradient fields.
- Particle image velocimetry of both the gas and liquid phases to determine the velocity fields, especially near the liquid surface.
- Infrared thermography of the fuel surface to determine extent of heated liquid flow.
- Point temperature and pressure measurements.
- The existing numerical model will be extended from two to three dimensions, gas-phase radiation will be accounted for, and explorations for including multi-step chemistry will begin. Detailed comparisons of the predicted flow and temperature fields will be undertaken.

Final Set:

- Gas-phase species measurements using a multi-channel line-of-sight absorption measurement technique.
- Higher framing rate camera (to 200 f/s) to measure small regions of rapid flow very near the liquid surface.
- Radiometer(s) to determine the flame radiation.

Test Environment: Flame spread will occur in a forced air flow ranging from 0 to 50 cm/s either co- or counter-current to the spread direction. Initial fuel temperatures from 10 - 40°C will be tested. The pressure should be maintained at 1 atm. Dry air will be the normal atmosphere, although it is expected that some tests will be conducted with various diluents (He, Ar, CO_2) and different O_2 concentrations. Accelerations less than 10 Hz should be less than 0.0005 g_o

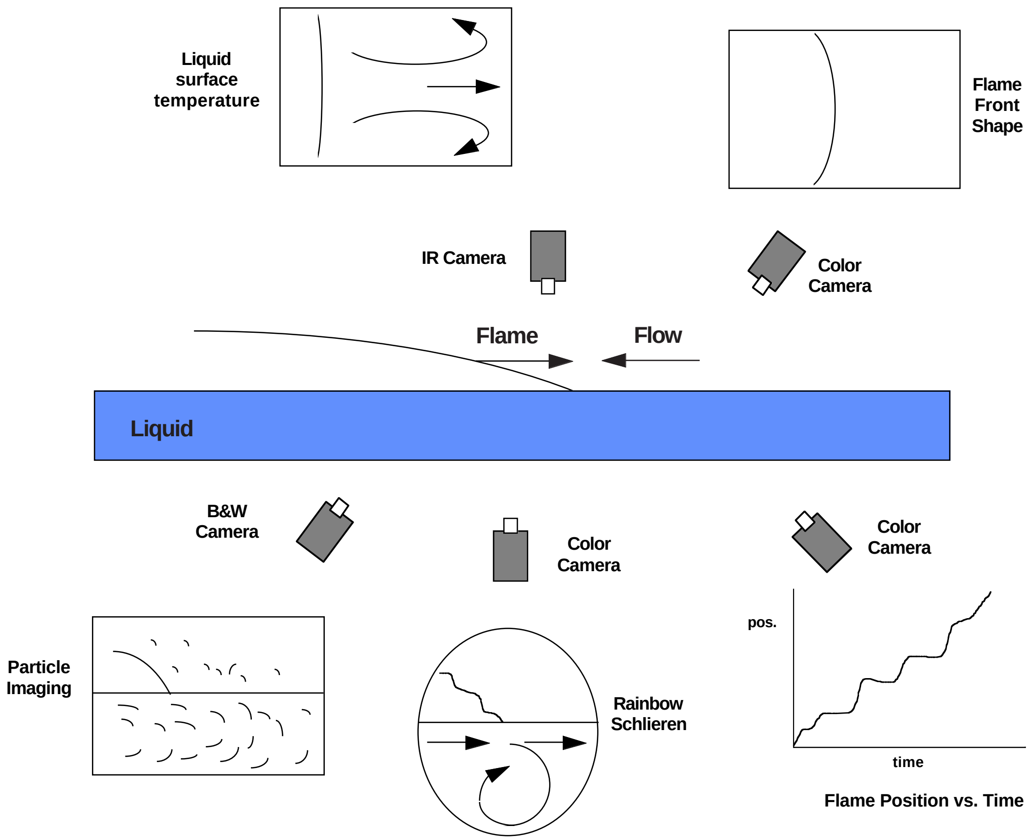
Test Matrix: Three different fuels (1-butanol, 1-propanol, and n-decane) will be tested, each at one or two initial temperatures. Three or four flow velocities in each direction are needed to adequately assess the forced flow effects. At this time, tests with a single fuel and temperature but varying O_2 concentrations and diluents are planned.

Special Considerations:

- Fuel tray must be filled right to the top (no freeboard) to assure a flat gas-liquid interface.
- Forced flow must be laminar and steady to within a few percent. No flow abnormalities such as recirculation can be tolerated in the duct.

Facing figure illustrates combustion basis experiment c3.

FLAME SPREAD ACROSS LIQUID POOLS (c3)



Flame Position vs. Time

B.2.4 Diffusive and Radiative Transport in Fires (c4)

Discipline Key Words: Combustion, solid fuels, flames spread rate, radiative transport, diffusive processes

Goals of Experiment: To analyze experimentally observed flames shapes, measured gas-phase field variables, spread rates, radiative characteristics, and solid-phase regression rates for comparison with theoretical prediction and to investigate the transition from ignition to either flame propagation or extinction in order to determine the characteristics of those environments that lead to flame evolution.

Principal Measurements/Observations Required:
Initial Set:

- side view to image flame spread, flame stand off, and flame radical species (OH and CH).
- infrared side view image to obtain spatial and temporal distributions of reactants (MMA) and product species (CO_2, H_2O, CO and soot) radiative emissions
- surface and in depth fuel temperature
- gas - phase temperature
- fuel surface radiative emissions
- temperature field measurements of the gas phase (side view)
- fuel surface temperature field

Final Set:

- velocity field measurements, possibly by particle imaging velocimetry (PIV) and point measurements at various heights above the sample surface

Test Environment: Polymethylmethacrylate (PMMA) samples will be burned in microgravity in low-speed (0-20 cm/sec) oxygen/diluent mixtures containing up to 70% oxygen. A uniform, radiant flux of up to 2 W/cm^2 will be imposed on the fuel surface.

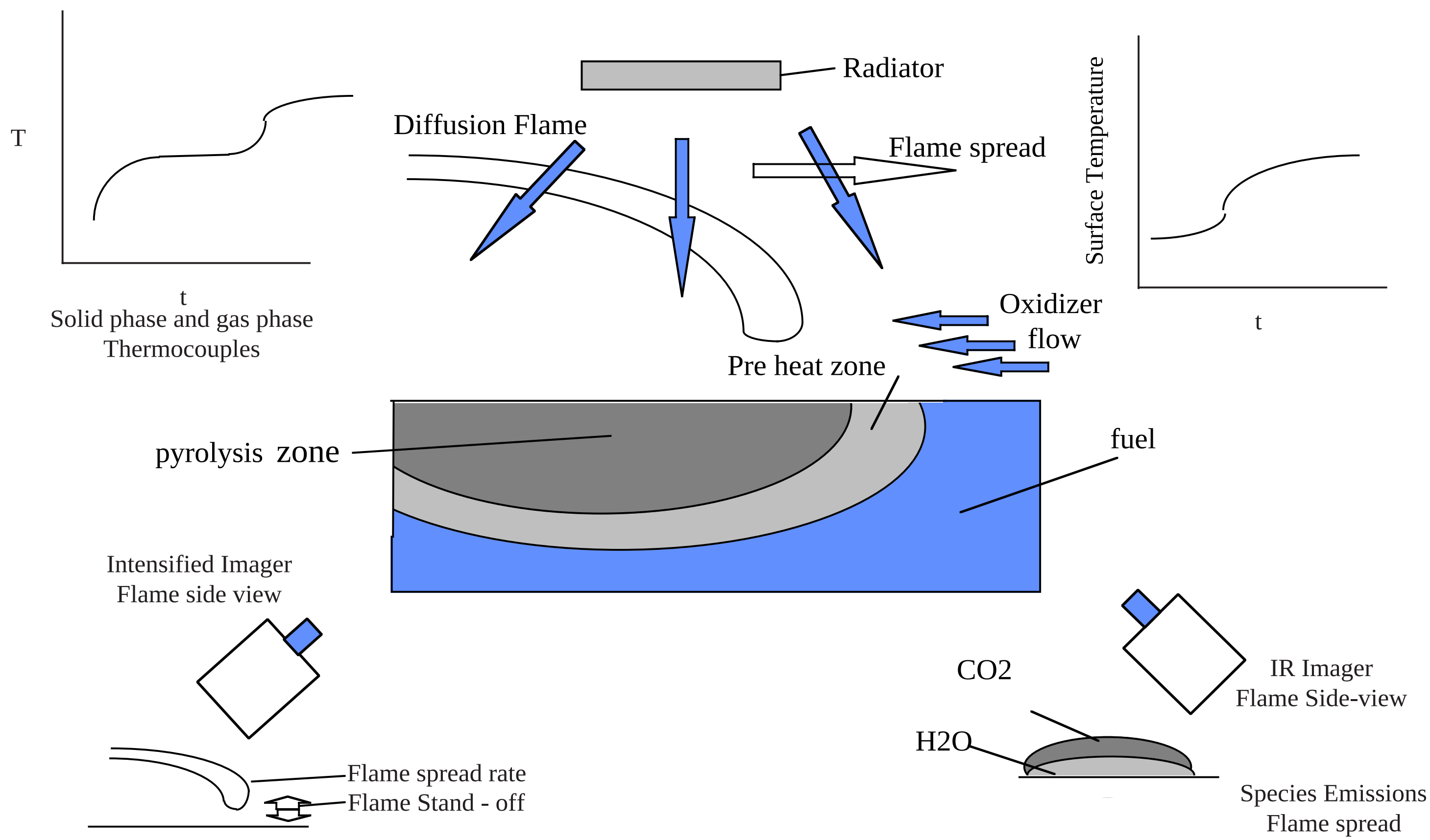
Test Matrix: Approximately 6-12 tests will be conducted to access the effects of flow and imposed radiant flux.

Special Considerations:

- Flames are dim in the visible spectrum and intensified imaging is required.
- Spatial resolution of the visible spectrum images is of the order 80-100 micron.
- Black body calibration of the infrared imaging device is needed for quantitative comparison with numerical models.

Facing figure illustrates combustion basis experiment c4.

DIFFUSIVE AND RADIATIVE TRANSPORT IN FIRES (c4)



B.2.5 Smoldering Combustion (c5)

Discipline Key Words: smoldering combustion, surface combustion

Goals of Experiment: To study the characteristics of smoldering combustion in microgravity

Principal Measurements/Observations Required:
Initial Set:

- Temperature measurements using thermocouples in the test chamber, at the igniter surface and in the interior of the sample
- Gas sampling near the fuel and desirably in the fuel interior with subsequent analysis for species identification
- Imaging of the fuel (top and side views) for observing the propagation of the smolder front

Final Set:

- Ultrasonic imaging of the smoldering sample during the experiment.

Test Environment: White, open-cell, non-flame retardant polyurethane foam of cylindrical and/or cubical shape (150-300 mm dia or side) will be burned at standard temperature and pressure conditions in various oxygen/nitrogen mixtures with low flow rates (0-5 mm/sec) both in the direction and opposite to the direction of the smolder front.

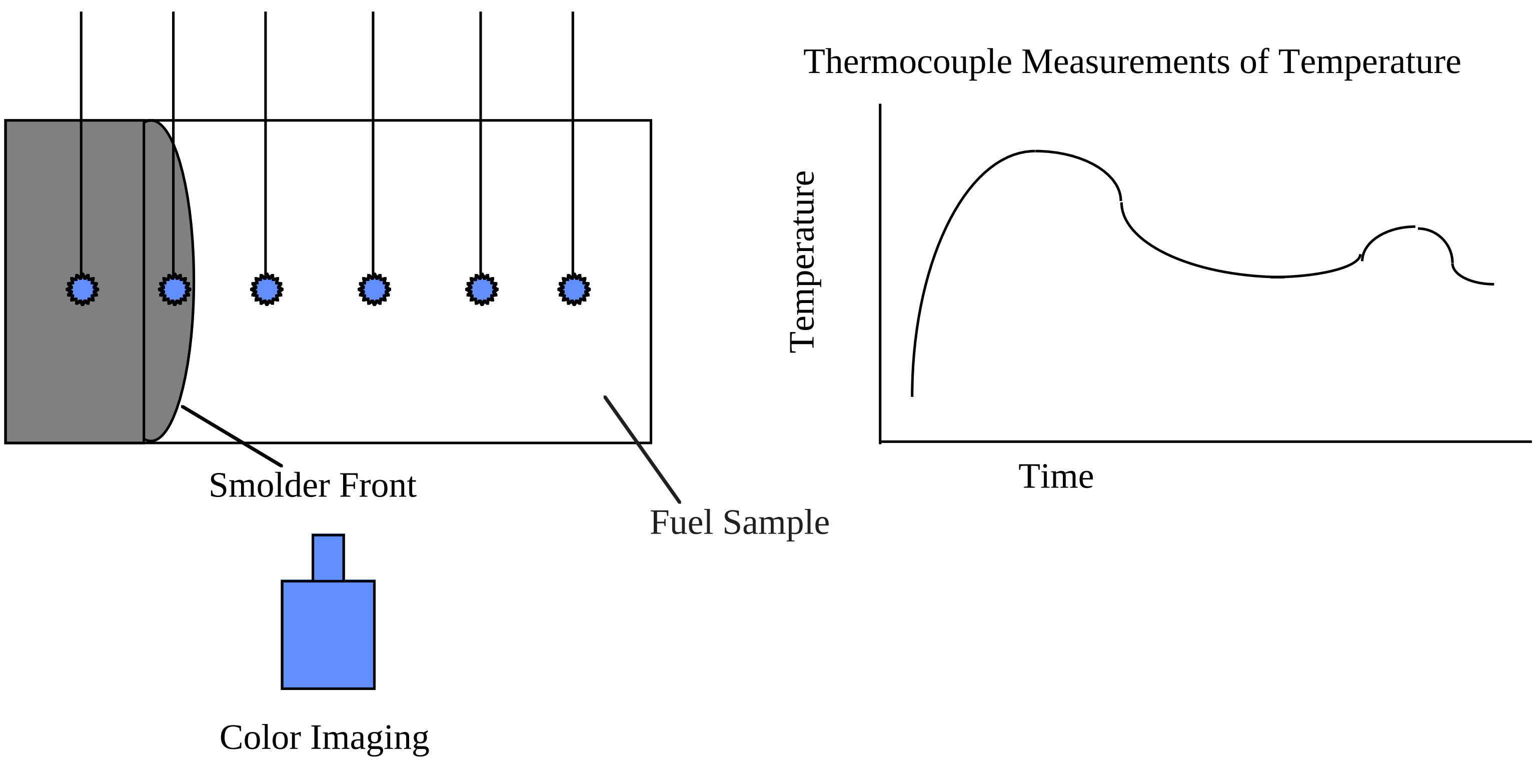
Test Matrix: Approximately ten tests will need to be conducted to properly characterize the variables of flow, flow direction and oxygen concentration.

Special Considerations:

- The products of smoldering combustion must be properly disposed
- The igniter characteristics must be carefully controlled to avoid flaming

Facing figure illustrates combustion basis experiment c5.

SMOLDERING COMBUSTION (c5)



B.2.6 Droplet Combustion (c6)

Discipline Key Words: droplet combustion, droplet diameter, extinction diameter

Goals of Experiment: To improve scientific understanding of droplet combustion, and in particular transient effects in the gas phase as well as the liquid phase and extinction phenomena. The data obtained will provide benchmark results against which to compare the predictions from various theoretical models.

Principal Measurements/Observations Required:

- High frame rate (to 100 frames/sec) backlit view of the droplet to obtain the droplet diameter time history
- Intensified imaging of the OH (310 nm) radical field to obtain the flame diameter as a function of time
- Color imaging of the experiment progress from droplet deployment and ignition to extinction
- Test chamber pressure and temperature
- Triaxial acceleration measurements

Test Environment: Droplets of liquid fuels such as n-heptane and methanol will be burnt in atmospheres containing between 10% and 50% oxygen in nitrogen and/or helium at initial pressures ranging from 0.25 to 1 atmosphere. The droplets will be freely deployed in most cases, however a few test points will be conducted with the droplets tethered to a fiber support.

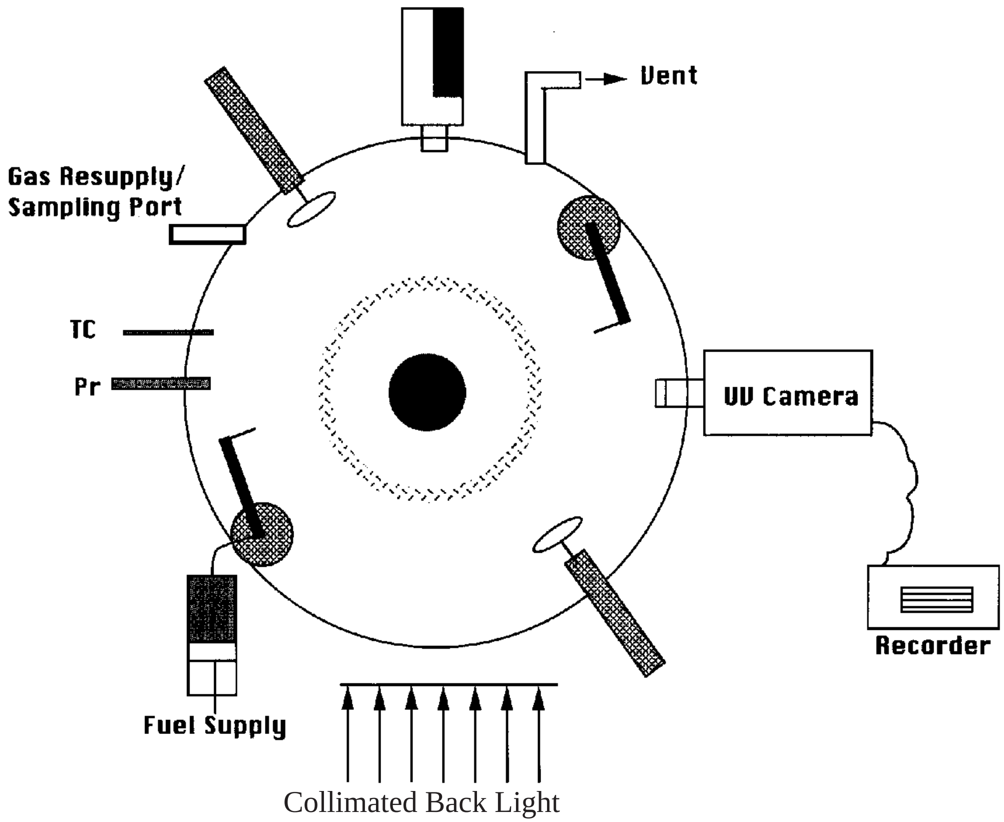
Test Matrix: Initial droplet diameters will be varied between 1.5 mm and 5 mm. Approximately 60-70 test points are needed in order to exercise the variations in the test operating conditions.

Special Considerations:

- The droplet diameter should be measurable to an accuracy of ± 18 microns and temporal resolutions on the order of 0.01-0.02 seconds.
- The imaging system must account for droplet drift perpendicular to the imaging plane

Facing figure illustrates combustion basis experiment c6.

DROPLET COMBUSTION (c6)



B.2.7 LAMINAR SOOT PROCESSES (c7)

Discipline Key Words: diffusion flame, soot, radiation

Goal of Experiment: to study the following:

- soot formation and oxidation rates
- soot aggregation rates
- soot volume fraction state relationships
- effects of continuum radiation from soot on flame structure and radiation properties in non-buoyant, soot-containing laminar diffusion flames

Principal Measurements/Observations Required:

- Soot volume fraction measurements by non-intrusive laser extinction, deconvoluting results for chord-like paths
- Soot temperature measurements using non-intrusive two wavelength pyrometry, deconvoluting results for chord-like paths
- Soot sampling with a thermophoretic sampling system
- Color imaging of the flame (side view)
- Temperature measurements in the fuel lean region outside of the flame using bare wire thermocouples

Test Environment: Gas jet diffusion flames of ethylene, propane, acetylene/nitrogen, and propylene/nitrogen will be burned in air at initial pressures in the range 0.5 - 1 atm.

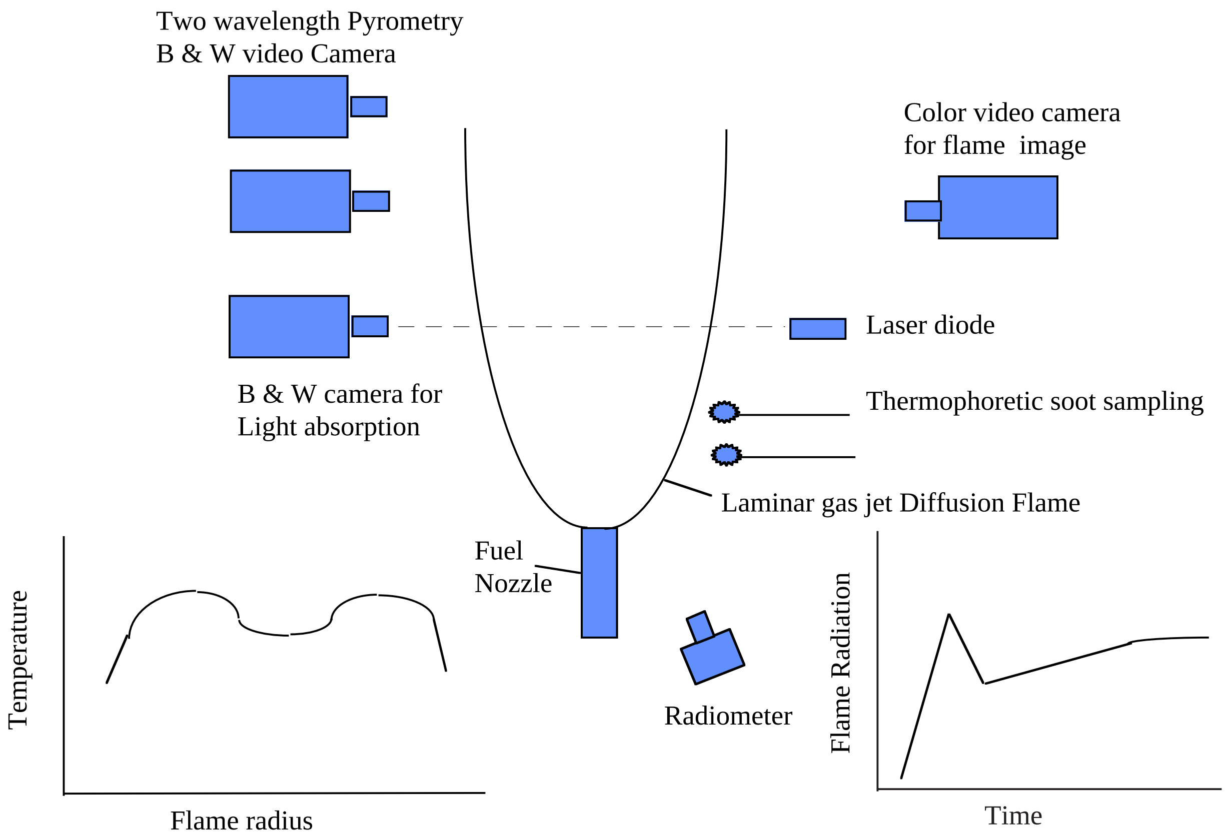
Test Matrix: The test matrix will vary fuel, flow rate (0.4 - 2 mg/sec), nozzle size, and initial pressure. The number of test points will be in the range of 10 - 15 in order to exercise the different variables.

Special Considerations:

- Apart from the soot sampler, there should be no intrusion of hardware into the vicinity of the flame.
- The maximum allowable consumption of oxygen within the combustion chamber is 10% by volume.

Facing figure illustrates combustion basis experiment c7.

LAMINAR SOOT PROCESSES (c7)



B.2.8 Soot Measurement in Droplet Combustion (c8)

Discipline Key Words: combustion, fuels, droplets, soot, microgravity

Goal of Experiment: To determine the effects of sooting on droplet combustion (burning rate, flame dynamics, extinction, disruption, and soot particle dynamics).

Principal Measurements/Observations Required:
Initial Set:

- Line-of sight extinction and subsequent 3-point Abel deconvolution determines the soot volume fraction distribution.
- Back-lit droplet image provides burning rate and extinction diameter data.
- Two-wavelength optical pyrometry determines the temperature of the flame.
- Thermophoretic sampling and subsequent transmission electron microscopy determines the soot morphology (radius of gyration, primary particle size, fractal geometry, etc.). Differential scattering experiments optically determine the radius of gyration of the soot aggregates.
- Computational modeling of the soot particle dynamics using the balance between thermophoresis and Stefan drag will be compared with the experimental measurements. The modeling efforts will be advanced interactively with the experimental measurements of the soot particle dimensions.

Eventual Set:

- Velocity measurement in the droplet vicinity.
- High frame rate digital video camera (1000 fps) to record laser back-lit view.
- Infrared camera to characterize ignition, uniformity of burning, and flame symmetry.
- Perform liquid fuel sampling during the burn.

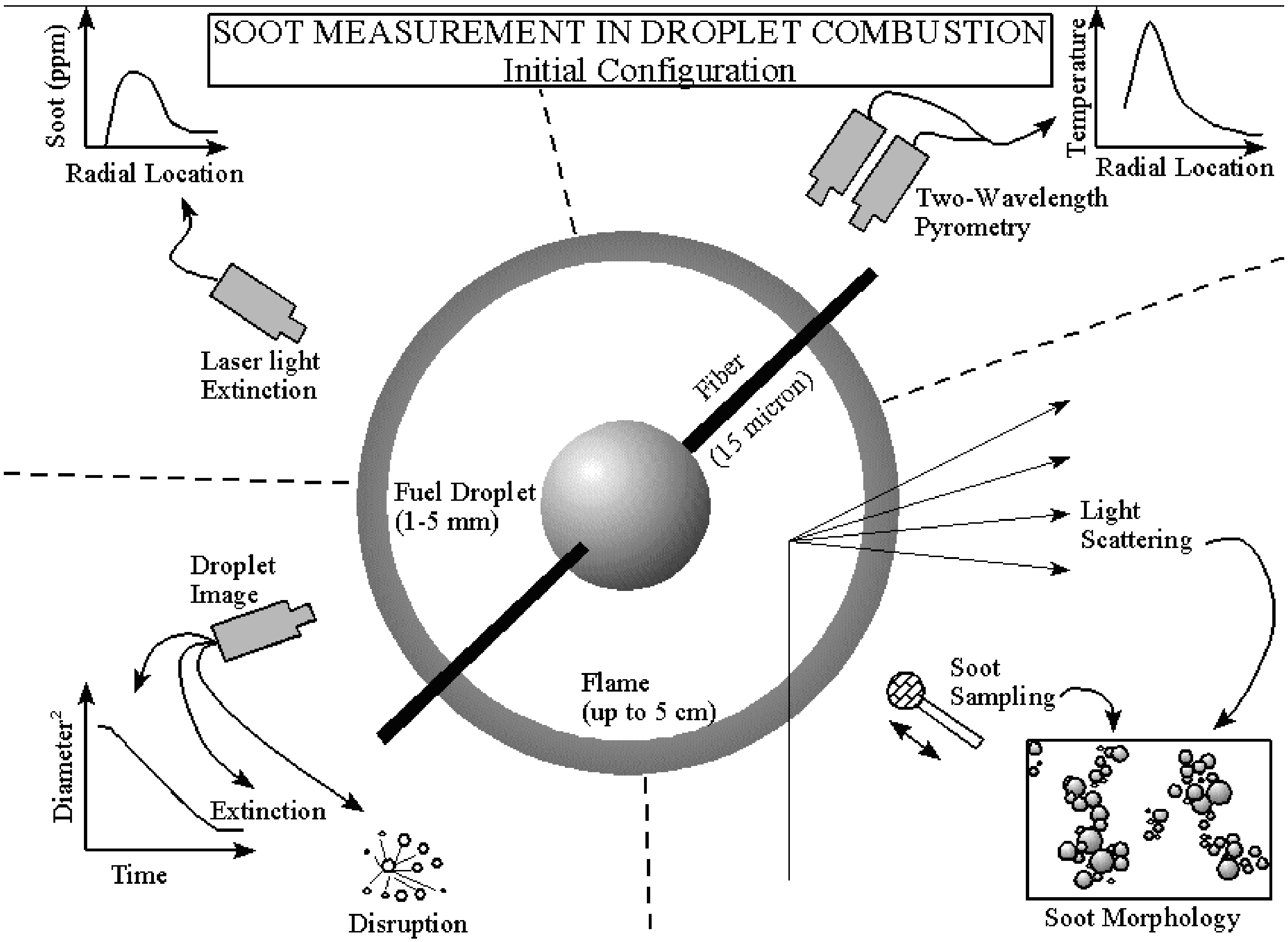
Test Environment: Droplets are to be burned in quiescent, microgravity, oxygen/diluent mixtures containing up to 50% oxygen, and ranging from 1/4 to 1 atm. total pressure. Diluents under consideration are nitrogen, helium, argon, and carbon dioxide. Initially, the gas should be at room temperature.

Test Matrix: Four oxygen/diluent mixtures, at three different pressures, and for different fuels and initial fuel droplet diameters will be investigated. Fuels under consideration include methanol, heptane, decane, toluene, methanol/toluene mixtures, and mixtures with a ferrocene additive. Initial fuel droplet diameters will vary from 1 to 5 mm.

Special Considerations:

- The droplet must be fiber-supported to permit diagnostic probing. This fiber must be very fine (about 15 microns) to prevent interfering with the combustion event.
- There is an exclusion zone required around the droplet to maintain spherical symmetry.
- Any intrusive diagnostic probing must be chosen carefully to minimize disturbing the flame.

Facing figure illustrates combustion basis experiment c8.


SOOT MEASUREMENT IN DROPLET COMBUSTION
Initial Configuration
Soot (ppm)
Radial Location
Temperature
Radial Location
Two-Wavelength
Pyrometry
Laser light
Extinction
Fiber
(15 micron)
Fuel Droplet
(1-5 mm)
Light
Scattering
Droplet
Image
Flame
(up to 5 cm)
Soot
Sampling
Diameter²
Extinction
Time
Disruption
Soot Morphology

B.2.9 UNSTEADY BURNING OF CONTAINED REACTANTS (c9)

Discipline Key Words: diffusion controlled combustion, traveling flames, unsteady flame, planar flame, burnout, microgravity

Goals of Experiment: to investigate the adequacy of frequently adopted, simplified mathematical models to describe the behavior of laminar flames, primarily diffusion flames, by comparison with definitive experimental data, conveniently available from burning in a microgravity environment

Principal Measurements/Observations Required:

- flame temperature profile in the range of 1700-2600 K using IR emissions from hot water molecules at 1.45 and 1.94 microns
- flame position and profile using IR emission.
- pressure inside the container (up to 10 atm)
- velocity profile in the container
- high speed imaging to characterize the flame propagation at ignition

Test Environment:

- A separator impervious to gas reactants divides the container into two equal subvolumes, containing initially quiescent fuel/inert and oxidant/inert gas mixture at equal temperatures, pressures and densities, until just before ignition.
- The separator is removed by rapid lateral translation in its own plane and the mixture is ignited after a short period of reactant interdiffusion. Separator removal and subsequent ignition must pose minimal disturbance to the gases. A planar diffusion flame is to form in microgravity and travel into deficient subvolume until burnout. Flame position, flame temperature and container pressure will be measured as a function of time.

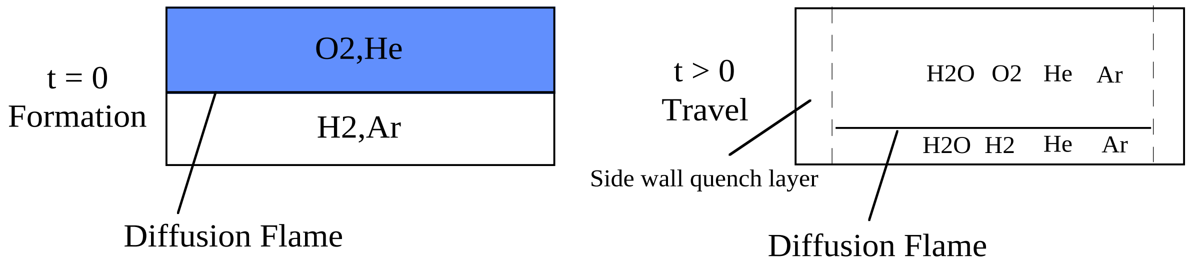
Test Matrix: Minimum of 20 tests will be conducted comprising of four different initial concentrations

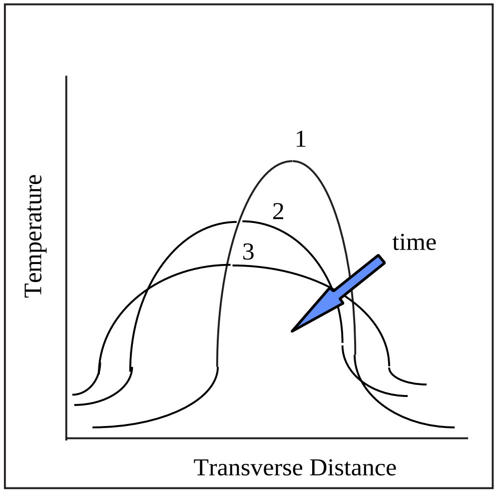
Special Considerations:

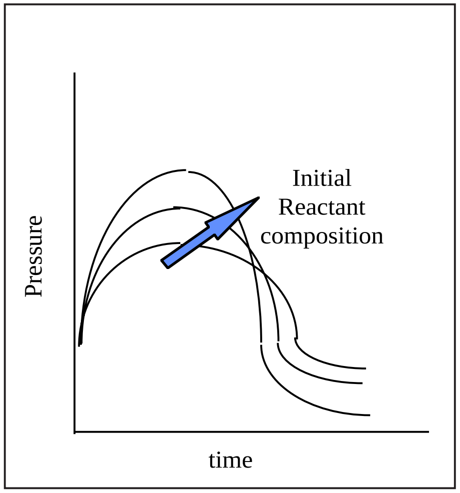
- The separator must be thin enough and removed fast enough to minimize disturbance for planar flame formulation.
- To simplify modeling, the container should ideally have a square cross section of greater than 20 cm on a side and a height of less than 10 cm.
- The pressure difference between the two subvolumes prior to separator removal must be less than 100 Pascal.
- Because the total thermal energy content of the reactants are small and the physical disturbances must be minimized the temperature measurement must be by non-intrusive optical techniques.

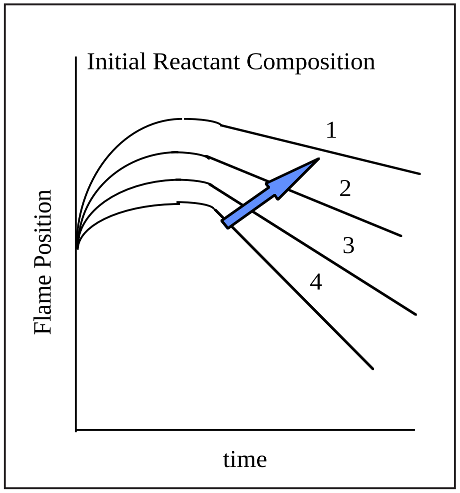
Facing figure illustrates combustion basis experiment c9.

UNSTEADY BURNING OF CONTAINED REACTANTS (c9)









B.2.10 FLAMMABILITY BOUNDARY OF SOLID FUELS (c10)

Discipline Key Words: combustion, solids, flammability, extinction, diffusion flames, modeling, diagnostics, microgravity

Goals of Experiment: To understand the flame spread and extinction phenomena of a thin combusting solid in low-speed forced concurrent flow.

Principal Measurements/Observations Required:

- Record inlet flow pressure, temperature, humidity, oxygen percentage, and flow speed during all tests.
- Measure fuel burnout rate.
- Determine radiation at a known solid angle (radiometry).
- Determine temperature at selected points (retractable thermocouple rake).
- Determine index of refraction gradient field using rainbow schlieren deflectometry.
- Image flame using UV camera to determine CH and OH emission fields.
- Determine temperature of flame using two-wavelength optical pyrometry and gas-phase IR imaging.
- Determine CO_2 and H_2O emission fields using gas-phase IR and verify absence of soot.
- Determine solid phase heat-up and pyrolysis temperature fields using IR image of fuel surface.

Test Environment: Thin sheets of solid fuel (paper, cloth, or polymer; 5 to 10 cm wide) will be burned in a low-speed forced concurrent flow in microgravity. The test atmosphere is oxygen/nitrogen mixtures at normal pressure and temperature.

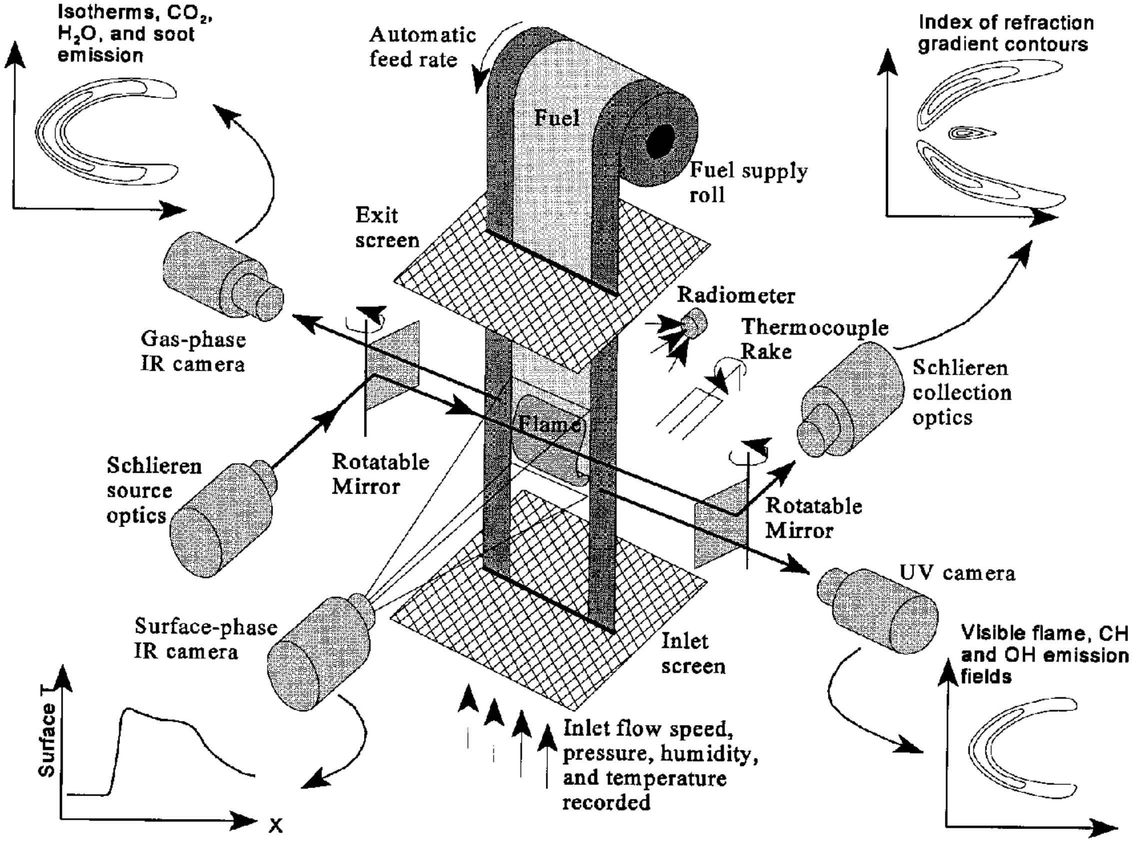
Test Matrix: Fourteen traverses will be performed with varying oxygen percentage at fixed flow speed of varying flow at fixed oxygen concentration. Percent oxygen will be varied from 10 to 21% and the flow speed will vary from 0 to 15 cm/sec. Some traverses will assess repeatability. One traverse will utilize a special reflective wall insert to determine the effect of radiation on flammability boundary.

Special Considerations:

- Substantial flow of oxidizer is required (up to 1 liter/sec for several minutes); real-time scrubbing of combustion products may be required.
- For cellulosic fuels, samples must be stored in dry atmosphere.
- Flame extinction is determined by decreasing flow and recording conditions at extinction.
- Manual extinguishing is required (e.g., halt flow, purge with N_2, or retract fuel).
- Wall temperature must be bounded.
- Walls and windows should have reflectivity <0.05 at wavelengths from 2 to 21 micron. Reflective wall insert must have diffuse reflectivity >0.5 in that range.
- Flame base must be fixed in space.
- Screens and filters in flow path should not inhibit flow.

Facing figure illustrates combustion basis experiment c10.

FLAMMABILITY BOUNDARY OF SOLID FUELS (c10)



B.2.11 RADIATIVE IGNITION AND FLAME GROWTH (c11)

Discipline Key Words: ignition, flame spread, radiation

Goals of Experiment: The overall objectives of this experiment are as follows:

- to conduct radiative ignition followed by transition to flame spread over various combustible solid surfaces in microgravity
- to understand the transition mechanisms from ignition to subsequent flame spread
- to determine the effects of oxygen concentration, external flow velocity, the size of the irradiated area, geometrical configuration, and sample materials on the transition and flame characteristics

Principal Measurements/Observations Required:

- Color images of the side view of the visible flame and the fuel surface (top view) for visualizing the char front
- IR images of the fuel surface (top view) to obtain the spatial and temporal distribution of the fuel surface temperature
- IR spectroscopic imaging (IRSA) with a spectral resolution of 15 nm from 2.2 microns to 4.6 microns over a 0.5 mm x 30 mm field of view to obtain the spatial, spectral and temporal distribution of gas-phase combustion products
- Collecting particulate products of combustion with TEM grids and particle filters for determining their characteristics and particulate yield of the flame.
- Temperature measurements in the solid and gas phase possibly by fine-wire thermocouples.

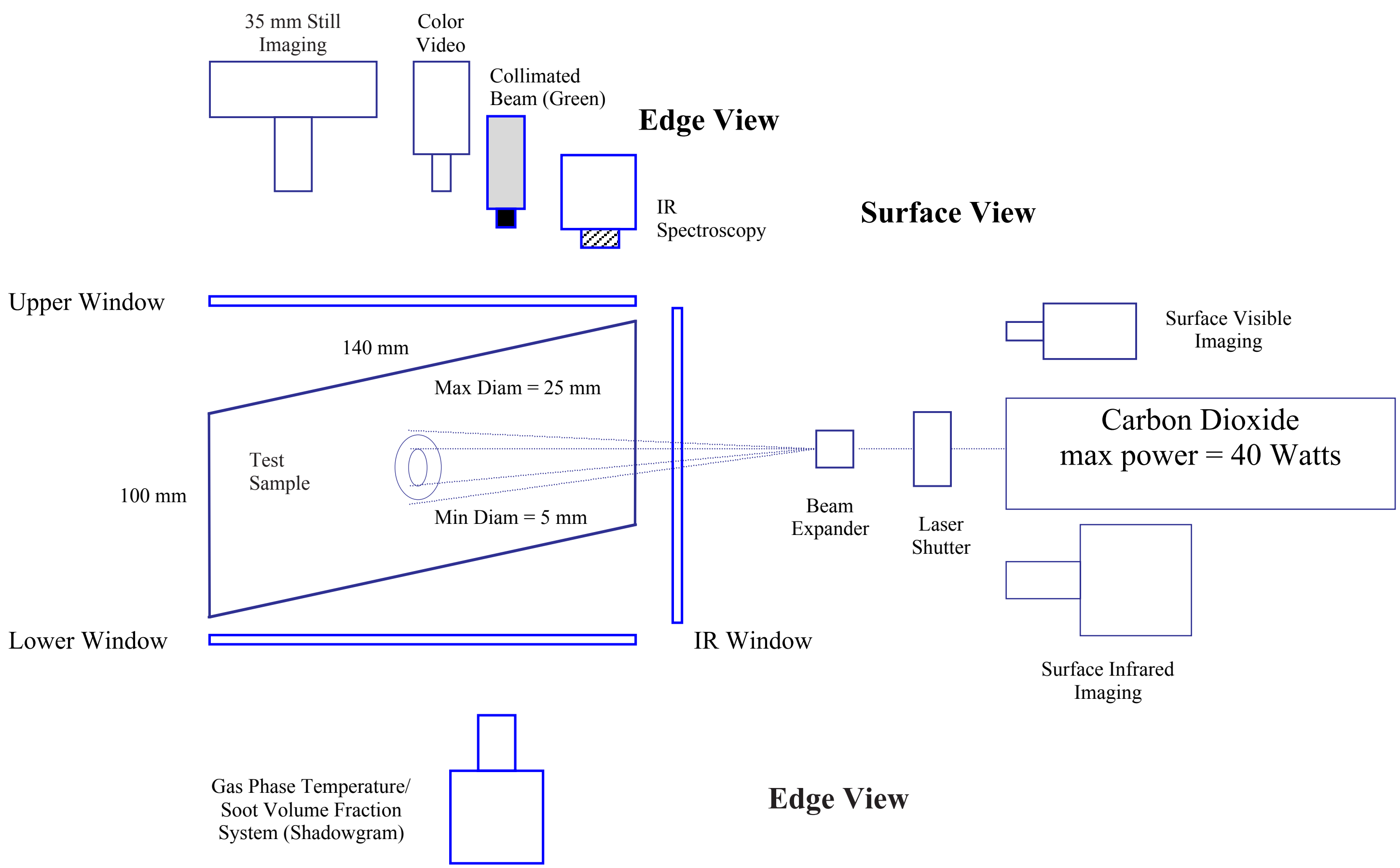
Test Environment: Various solid fuels (e.g., charring filter paper, non-charring polyethylene, and PMMA) in different configurations (e.g., 2-D, 3-D, axisymmetric) will be burnt in atmospheres of 21%-50% oxygen convecting between 0-20 cm/sec. Ignition will be accomplished by a radiant source which will irradiate the fuel surface over a radius between 0.5-1.2 cm.

Test Matrix: Approximately 20 test points are needed in order to exercise the variables of fuel type, oxygen concentration, geometry, and ignition area.

Special Considerations:

- The flux of the radiant ignition source (a CO_2 laser is suggested) is to be measured.
- The IR cameras are to be calibrated with a black body device.

RADIATIVE IGNITION AND FLAME GROWTH (c11)



Appendix C - Space Station Constraints

C. SPACE STATION CONSTRAINTS

It must be kept in mind that several primary resources provided by the International Space Station (ISS) are limited by availability and have demands from users beyond the FCF. Similarly, severe constraints on launch capabilities will limit the volume and mass of FCF scientific and support hardware that can be placed on orbit. While it is strongly desired that such constraints be diminished in the future, it is obvious that the initial capabilities will be constrained by existing services.

The types and ranges of key services defined by launch and ISS capabilities are summarized in the facing figure.

SPACE STATION (RESOURCE ENVELOPE FOR FCF)

Resourc	Units		Low	Expecte
Rack upmass	kg/rack		500	700
Resupply Flights	per year		2	4
Resupply Upmass	kg/flight		150	300
Power	watts	typical	1,000	2,000
Power	watts	peak	2,000	6,000
Thermal Water	kg/hour		28	56
Energy	kw-hr/year		4,500	9,000
Crew Time	hour/week		1	4
Crew Time	hour/year		50	200
Microgravity			ARIS*	ARIS*
Powered Racks	rack		3	3
Unpowered Stowage	rack		0.25	1
Communication	Mbits/sec	typical	1	3
Communication	Mbits/sec	maximum	10	20
Communication	Gbytes/day		7	20

* Active Rack Isolation System for one or both experiment racks

Appendix D - Summary Table of Science Requirements, Desired Capabilities, and Compliance Verifications

D. SUMMARY TABLE OF SCIENCE REQUIREMENTS, DESIRED CAPABILITIES, AND COMPLIANCE VERIFICATIONS

PREFACE

Appendix D summarizes the FCF science requirements and Desired Capabilities. In addition, it suggests top level approaches to verifying FCF compliance.

Science requirements are given in their most succinct form in this Appendix. Due to the succinct format, the requirements are not fully expressed here. In particular, the charts and graphs in the body of the SRED are intended to be a graphical and more complete statement of each requirement. These charts (graphical statements) have more weight than the words in the associated text because they define envelopes, or areas of performance. The facility must be adaptable within a range of performance as indicated by the envelope charts which are not reproduced here.

Compliance to science requirements must be shown by the completed facility. In this Appendix, suggested compliance criteria are associated with the requirements. Generally, the approach to indicating compliance centers on analysis of FCF's ability, augmented by PI hardware, to perform the Basis Experiments while providing the capabilities implied by the science requirements. Subsequently, the completed hardware shall be tested to verify the hardware performance assumed for the analyses.

For many requirements, compliance can be inferred from analysis of the FCF detail design and a few tests. For example, the ability to read a given number of A/D channels to a given precision can be confirmed by indicating the presence of the required A/D hardware combined with an as-installed (in the flight unit) test of the A/D hardware & software which indicates the needed accuracy, precision, absence of noise, and etceteras. On orbit, how the channels will be used and perform depends on a particular experiment implementation and PI hardware which is unknown; therefore, a more specific evaluation is not justifiable.

For some requirements, compliance involves proving that FCF can be set up, including the PI hardware and operations concept, to perform a generic class of experiment while meeting the requirement. Often, geometry and available volume limit what can be accomplished. In these cases compliance shall be indicated by conceptually laying out an appropriate subset of the Basis Experiments (described in Appendices A and B) in the FCF racks (on paper or in a computer model) and demonstrating (by analysis) that the experiments' requirements could theoretically be met using the conceptual layout. Of course, the relevant FCF flight components must be tested to prove that they individually perform to the standard assumed for the analysis. The experiment layout concepts and analyses shall be best efforts. It is strongly suggested that concepts be developed for all the Basis Experiments. These concepts can be reused to show compliance to each requirement and requirement envelope.

Appendix D - Summary Table of Science Requirements, Desired Capabilities, and Compliance Verifications

D.1 REQUIREMENTS AND COMPLIANCE CRITERIA

1.0 - FCF Level 1 Requirements

1.2 - FCF MISSION AND PERFORMANCE REQUIREMENTS

1.2.1 - FCF Mission Requirements

Req. P1 - The Fluids and Combustion Facility (FCF) shall be a permanent on-orbit research facility located inside the United States Laboratory Module (US Lab) of the International Space Station (ISS). FCF shall support NASA Human Exploration and Development of Space (HEDS) Microgravity Program objectives. In particular, FCF shall accommodate and facilitate *sustained*, *systematic* Microgravity Fluid Physics and Microgravity Combustion Science experimentation on the ISS for the lifetime of the ISS.

Req. P2 - Fluid Physics and Combustion Science shall be of equal relative priority within the scope of FCF planning, design, operations, and other activities.

Req. P3 - FCF shall plan to occupy no more than 3 International Standard Payload Racks (ISPR) located in the US Lab module plus up to 1 additional rack of un-powered stowage, as needed to meet the Level 1 requirements.

Req. P4 - FCF Level 1 requirements shall take precedence over other scientific and technical requirements.

1.2.2 - FCF Fluid Physics Performance Requirements

Req. P5 - As ISS and FCF resources become available, FCF shall permit a utilization rate of at least 5 *Basis Experiment* type fluid physics experiments per year while remaining within FCF and ISS resource constraints as understood at the FCF Requirements Definition Review (RDR); however, FCF shall be designed to support a utilization rate of 10 fluid physics experiments per year, should resources permit. FCF compliance to this requirement shall be shown by an analysis indicating that a majority of Fluid Physics *Basis Experiments* could be flown on FCF at a rate of 5 per year within budgetary and ISS resource constraints.

Req. P6 - As ISS and FCF resources become available, FCF shall accommodate at least 80 percent of the microgravity fluid physics experiments likely to be proposed for FCF. FCF compliance shall be shown by conceptual experiment layouts and analysis indicating that 80 percent of the fluid physics *Basis Experiments* could be accommodated by FCF facility capabilities when augmented by PI hardware capabilities.

Req. P7 - To accommodate potential commercial and international users, FCF shall accommodate at least 5 additional (in addition to Req. P5) fluid physics experiments per year, assuming that PI hardware and other required resources are provided by those users.

1.2.3 - FCF Combustion Science Performance Requirements

Req. P8 - As ISS and FCF resources become available, FCF shall permit a utilization rate of at least 5 *Basis Experiment* type combustion science experiments per year while remaining within FCF and ISS resource constraints as understood at the FCF Requirements Definition Review (RDR); however, FCF shall be designed to support a utilization rate of 10 combustion science experiments per year, should resources permit. FCF compliance to this requirement shall be shown by an analysis indicating that a majority of combustion science *Basis Experiments* could be flown on FCF at a rate of 5 per year within budgetary and ISS resource constraints.

Req. P9 - As ISS and FCF resources become available, FCF shall accommodate at least 80 percent of the microgravity combustion science experiments likely to be proposed for FCF. FCF compliance shall be shown by conceptual experiment layouts and analysis indicating that 80 percent of the combustion science *Basis Experiments* could be accommodated by FCF facility capabilities when augmented by PI hardware capabilities.

Req. P10 - To accommodate potential commercial and international users, FCF shall accommodate at least 5 additional (in addition to Req. P8) combustion science experiments per year, assuming that PI hardware and other required resources are provided by those users.

1.3 FCF BASIS EXPERIMENT DEFINITION

1.3.2 Fluid Physics Basis Experiments

Req. P11 - The Fluid Physics Basis Experiments shall be precisely the 16 experiments listed in Table P11.

1.3.3 Combustion Science Basis Experiments

Req. P12 - The Combustion Science Basis Experiments shall be precisely the 11 experiments listed in Table P12.

1.3.4 FCF Requirement Envelope Definition Rules

Req. P13 - The FCF Science Requirements Envelope Document (SRED) shall present Basis Experiment requirements collectively.

Req. P14 - The FCF developer shall consider the requirements of a given type collectively in formulating concepts and approaches to compliance. Extreme requirements for single experiments should not bias the compliance in a manner that adversely affects integrity or cost effectiveness of the design.

Req. P15 - The FCF project's highest priority shall be to meet requirements followed by implementing desired capabilities. Implementation of *suggestions* included in the accompanying text need not have priority in shaping the compliance response; however, such suggestions should be seriously considered while making trade-off decisions for alternative approaches to compliance.

1.3.4.1 Criteria for Definition of Requirements

Req. P16 - To be an FCF science requirement an item shall meet the following minimum criteria:

1. The requirement shall be stated as (or be interpretable as) a functional capability. Examples: a requirement could be stated as an ability to measure a given parameter with a given accuracy, or a requirement could be stated as a capability to provide laser lighting at certain wavelengths and power levels.
2. At least one Basis Experiment will fail if the requirement is not met. The burden of proof regarding this criterion is on the person or group proposing the requirement.
3. Inspection, analysis, or test can objectively verify how well FCF meets the requirement. An acceptable verification method can be *suggested* as part of the requirement; however, the FCF developer may elect to use a different verification method.

1.3.4.2 Criteria for Definition of Desirable Capabilities

Req. P17 - To be a valid FCF desired capability or feature an item shall meet the following minimum criteria:

1. Does not qualify as a requirement.
2. Supported by objective data indicating that at least two Basis Experiments would have substantially greater scientific yield if the desired capability were implemented. The burden of proof regarding this criterion is on the person or group proposing the capability or feature.
3. Inspection, analysis, or test can objectively verify how well FCF provides the capability. An acceptable verification method can be *suggested*; however, the FCF developer may elect to use a different verification method.

1.3.4.3 Suggested Engineering Implementations

Req. P18 - Specific technologies or engineering solution verbiage associated with the FCF science envelope requirements do not constitute requirements on the FCF project team to implement that technology or solution.

Req. P19 - The FCF developer shall endeavor to ascertain the underlying functional requirement implied by a suggested implementation and meet that functional requirement – provided that the implied requirement meets Req. P16. The developer shall use similar logic for implied desired capabilities which shall meet Req. P17.

Req.P20 - Compliance to science requirements must be shown by the completed facility. Generally, the approach to indicating compliance centers on analysis of FCF's ability, augmented by PI hardware, to perform the Basis Experiments while providing the capabilities implied by the science requirements. Subsequently, the completed hardware shall be tested to verify the hardware performance assumed for the analyses.

Appendix D - Summary Table of Science Requirements, Desired Capabilities, and Compliance Verifications

2.0 - FLUIDS REQUIREMENT ENVELOPES

2.2 - EXPERIMENT OPERATING ENVIRONMENT

2.2.1 - Physical Environment

Req. F1 - FCF shall provide a work volume dedicated to Fluid Physics experimentation. A majority of this volume shall nominally be set aside for PI hardware that may be unique to a specific experiment. Compliance involves showing by analysis and/or conceptual layout that 80 percent of the fluid physics basis experiments could be accommodated within the work volume. The volume set aside shall be adequate to accommodate at least 80% of the Fluid Physics Basis Experiments.

Req. F2 - FCF shall be capable of accommodating fluid physics PI hardware test cells and containers in the range of sizes and capabilities required by the basis experiments. This requirement will be met if FCF can show by analysis and/or conceptual layout that 80 percent of the fluid physics basis experiments, including the necessary PI hardware test cells and containers for those experiments, could be accommodated by FCF.

Req. F3.1 - FCF shall be capable of providing a microgravity environment (at the test sample) that accommodates the envelope of limiting accelerations identified for the fluid physics basis experiments. Operational protocols may be used to support compliance with this requirement (e.g., scheduling to avoid major disturbances). Figures F3a and F3b are graphical statements of the requirements to be enveloped. Figure F3a illustrates the approximate upper limits on quasi-steady acceleration for each basis experiment. Figure F3b illustrates the excluded zone for g-jitter. Operational protocols may be used to assist meeting this requirement (e.g., time lining to avoid major disturbances).

Req. F3.2 - FCF shall accommodate an acceleration measurement device as close as practical to the test cell. It shall be capable of measurements in three simultaneous orthogonal directions at levels from 10^{-2} to 10^{-6} g/g_0 and frequencies from 0.01 to 300 Hz. Accuracy shall be within 10 percent of selected full scale acceleration range. The data shall be available in near real time and post mission**.** Analysis and test shall be used to verify compliance with this requirement, if SAMS-II is not used.

Req. F4.1 - FCF shall provide stable temperatures within the fluid physics work volume in the range of 20 to 30 C during periods of operation. Analysis and test shall be used to verify compliance with this requirement.

Req. F4.2 - The facility shall support the ability of PI hardware to maintain required test cell (and other) temperatures inside the PI hardware over a minimum range of -20 to 100 C. Analysis and test shall be used to verify compliance with this requirement.

Req. F5 - FCF shall provide the capability to control air circulation within and around measurement systems that are susceptible to disturbance caused by uncontrolled air circulation. At times the air must be still and at times it must be circulated to obtain relatively uniform conditions. PI hardware can be used to control air circulation for particularly susceptible experiments. Layout concepts, analysis, and tests shall be used (as needed) to verify that uncontrolled air circulation will not disturb measurements required by the majority of fluid physics basis experiments.

Req. F6 - FCF shall provide physical and procedural controls to limit levels of contamination on the optical elements of optical systems during handling, setup, operation, and storage. Optical element transmission shall remain greater than 60 percent of the day 1 value (previously verified). Replacement of contaminated elements can be used as one aspect of control. Analysis and test shall be used to verify compliance with this requirement.

2.2.2 - Resources

Req. F7.1 - FCF shall provide PI-provided hardware with adequate power per the estimates shown in figure F7. Analysis shall be used to verify compliance with this requirement. At least 400 W shall be provided.

Req. F7.2 - FCF shall provide 5 (or more) individually controlled sources of electric power for use by PI hardware (minimum capability would be five 28 volt, 4 amp circuits). Analysis shall be used to verify compliance with this requirement.

Req. F7.3 - FCF shall provide PI hardware with easy access to cooling adequate to dissipate the power provided to the PI hardware. Access to both liquid cooling and air cooling is required. Analysis shall be used to verify compliance with this requirement.

Req. F8 - FCF shall provide uniform, broad band lighting (nominally white light) at the test cell. Intensity and uniformity shall be consistent with image resolution requirements. The absolute mean intensity shall be variable over a wide range. The mean intensity shall be determinable with an accuracy of approximately 1 percent before, during, and after an experiment test point run. The mean intensity shall be stable within approximately 1 percent during a test point run. The dimensions of the illuminated area shall be capable of adjustment over a range of sizes as required by the basis experiments; however, the nominal size shall be an approximately 10cm x 10cm illuminated field of view. Analysis and test shall be used to demonstrate that FCF provided lighting meets the appropriate requirements of the majority of fluid physics basis experiments. It is suggested that the standard deviation of the intensity across the whole area not exceed 1 percent. It is suggested that to obtain the standard deviation, the central 90 percent of the useful field area will be divided into contiguous sub-fields and the intensity of each sub-field will be used to determine the mean and standard deviation of the illuminated field. The area of each sub-field should not exceed 1/250,000 of the total useful field area. Since the intensity will be variable, the standard deviation should be determined at a number of intensities spanning the range of useful intensities. Lens systems used by the broad band lighting system may cause a “curvature” or predictable variation in the nominal intensity across the field. Curvature effects (up to 5 percent of the mean) can be factored out of the intensity standard deviation, if the PI can predict intensity with 1 percent accuracy.

Req. F9.1 - FCF shall provide laser sources, optical systems, power, and control to enable laser illumination over the range of wavelength, polarization, power, and other characteristics required by the majority of fluid physics basis experiments. The facility shall provide collimated beams and light sheets having adjustable size and position. Laser light sources used for background lighting shall be subject to the same intensity uniformity standards as the broad band background lighting sources (req. F8). Analysis and test shall be used to verify compliance with this requirement.

Req. F10 - FCF shall provide PI hardware access to the ISS vacuum vent system. Conceptual layouts and analysis shall be used to verify compliance with this requirement.

Req. F11 - FCF shall provide on-orbit stowage volume having power and cooling to accommodate such needs as thermal control, stirring, and tumbling of experiment samples whenever required. Conceptual layouts and analysis shall be used to verify compliance with this requirement.

2.2.3 - Test Points and Test Duration

Req. F12 - FCF shall accommodate the quantity of test points and test point durations of the fluid physics basis experiments per the estimates in figure F12. Compliance shall be verified by analysis that shows that the majority of basis experiments can be time lined to meet their minimum requirements for test points and duration while maintaining an adequate microgravity environment during each test point.

2.3 - EXPERIMENT MEASUREMENT CAPABILITIES

2.3.1 - Imaging Capabilities

Req. F13.1 - FCF shall provide a set of imaging capabilities (e.g., subassemblies incorporating cameras, lenses, mirrors, et al) covering, nominally, the entire visible light spectrum. They shall be the types and quantities required by the basis experiments. Compliance shall be verified by camera tests and analysis that shows the FCF provided cameras, in combination, meet the requirements of the majority of the fluid physics basis experiments.

Req. F13.2 - FCF shall accommodate PI-provided cameras and supporting hardware which are compatible with power, data acquisition, and work volume capabilities.

4.3.2 - Optical Interfaces

Req. F14.1 - FCF shall accommodate simultaneous imaging of the test cell from at least two orthogonal directions as required by the basis experiments. This requirement will be met if FCF can show by conceptual layout that the fluid physics basis experiments requiring orthogonal viewing could be accommodated within the dedicated fluid physics volume.

Req. F14.2 - FCF shall provide downlink for at least two imaging channels in near real time with frame rate and resolution adequate to monitor the progress of the test point, for image analysis, and for interactive control of the basis experiments. Compliance shall be verified by end-to-end (i.e., camera to ground terminal) pre-flight tests, data transmission analysis, and science need analysis (i.e., how the scientist will use the near real time data) that shows the FCF could meet the requirement for the majority of fluid physics basis experiments that require downlink of two imaging channels.

Req. F15.1 - FCF shall provide positioners, optical systems, power control, and procedures to reproducibly position and align light sources, optics, and other experimental components located within the dedicated fluid physics volume. The relative positions of components shall be reproducible and knowable with the accuracy and precision required by the majority of basis experiments. Analyses, set up, and measurement of at least 3 representative component arrangements (based on layout concepts for the basis experiments) shall be used to verify compliance with this requirement.

Req. 15.2 - Position and alignment adjustment of PI-provided optical components with a precision of approximately a micron or less relative to other optical components shall be supported by the FCF system, as required for practical implementation of the basis experiments. Analyses, set up, and measurement of at least 3 representative component arrangements (based on layout concepts for the basis experiments) shall be used to verify compliance with this requirement.

2.3.3 - Optical Measurements

Req. F16 - FCF imaging shall accommodate the ranges of field of view and resolution necessary to support the basis experiments per the estimates in figure F16. Figure F16 is a graphical statement of the requirements to be enveloped. Compliance shall be verified by analysis of conceptual layouts of some basis experiments. Compliance shall be illustrated by plotting the envelope of FCF field of view versus resolution (predicted by analysis) on Figure F18. If the majority of experiments (having a resolution requirement >3 micrometers) are substantially enclosed by the envelope, then FCF meets the requirement. Substantially enclosed means that the area representing the experiment (on Figure F18) is more than 80 percent enclosed. Because the scientific requirements involve some uncertainty, high precision in proving that 80 percent is enclosed is not justified; empirical evaluation shall be sufficient.

To develop the FCF envelope, use the following procedure and definitions. Using conceptual basis experiment layouts, the ranges of field of view and resolution shall be predicted for hypothetical objects, in focus, located at the center of the test volume or test cell. The ranges shall be plotted on Figure F18. The outer extents of the ranges shall be joined by straight lines to form the FCF envelope. Using this method, only the extreme cases need be analyzed.

For fixed lens systems that do not track the object of interest, the size of the field of view shall be defined as the smaller of two quantities: 1. Diameter of the circular region imaged by the lens system onto plane of the camera sensor (e.g., film or CCD) divided by the magnification of the optical system; or, 2. The largest dimension of the camera sensor active area (height or width) divided by the magnification of the optical system.

If automatic particle tracking is assumed, then the field of view shall be determined as the diameter of the entire planar region visible to the camera sensor (at the center of the test volume) as it is scanned to its practical limits. If the region is not circular, then calculate a pseudo diameter using its area as though it was circular. The practical scanning limits of FCF supplied systems must be established by test using flight type hardware/software and target objects having the contrast, size, and velocities expected of the scientific phenomena.

Resolution shall be calculated as the larger of two quantities: 1. The theoretical Airy limiting resolution of the image projected on the camera sensor divided by the magnification of the optical system; or, 2. The center to center distance between camera pixel elements divided by the magnification of the optical system. For cameras using film as the sensor, the film pixel element center to center distance shall be defined as 10 micrometers. This method shall be used for both fixed lens systems and systems using automatic particle tracking. The lowest (best) resolution value claimed by FCF and plotted on Figure F18, shall be verified by testing flight like optics and cameras configured as in the concept which was analyzed to establish the best resolution.

Req. F17 - FCF shall accommodate the range of fields of view (FOV) and expected particle velocities required by the basis experiments per the estimates in figure F17. Figure F17 is a graphical statement of the requirements to be enveloped. Compliance shall be verified by analysis of conceptual layouts of some basis experiments. Compliance shall be illustrated by plotting the envelope of FCF field of view versus particle velocity (predicted by analysis) on Figure F19. If the majority of experiments are substantially enclosed by the envelope, then FCF meets the requirement. "Envelope" and "substantially enclosed" have the same meaning as in F18, above.

Fields of view shall be as determined in F18. The easiest way to assure this is to analyze the same conceptual optical layouts as used in F18.

The conceptual optical layouts shall meet the resolution criteria of F18. The easiest way to assure this is to analyze the same conceptual optical layouts as used in F18.

For fixed (non tracking) optics, the effective maximum velocity that can be accommodated is a function of exposure duration (for a single image) and the required resolution of the image as indicated in F18. Assuming the object is in the planar region defined in F18, the maximum velocity is given by: (one-half) times (required resolution) divided by (exposure duration). Exposure duration is determined by how long the camera sensor is exposed to light that causes an imaging response – this varies with camera settings and illumination method.

For automatically tracking optics, the procedure above may be used to determine a conservative value for maximum velocity. Claims of higher velocity due to the tracking system (which minimizes the relative motion of the image and the sensor) must be verified by tests. The practical velocity limits of FCF supplied systems may be established by test using flight type hardware/software and target objects having the contrast, size, and velocities expected of the scientific phenomena.

Req. F18 - FCF shall provide the range of framing rate and range of quantities of images required by the basis experiments per figure F18. Compliance shall be illustrated by plotting the envelope of framing rates and quantity of images on Figure F20. If the majority of experiments are substantially enclosed by the envelope, then FCF meets the requirement. "Envelope" and "substantially enclosed" have the same meaning as in F18, above.

Fields of view shall be as determined in F18. The easiest way to assure this is to analyze the same conceptual optical layouts as used in F18.

The conceptual optical layouts shall meet the resolution criteria of F18. The easiest way to assure this is to analyze the same conceptual optical layouts as used in F18.

Evaluation of FCF framing rate shall include camera performance, light source performance, optical system light transmission performance, computer system and storage system performance, etceteras. Evaluation of FCF ability to store frames shall consider scientifically required resolution, total images actually required per experiment run, and other practical factors.

The claimed framing rates and image storage capacity shall be verified by tests of flight like hardware operating as conceptually proposed for some of the basis experiments.

Req. F19.1 - FCF shall provide at least one removable media recording device capable of recording the equivalent of 2 hours of standard video data. Compliance shall be shown by analysis of the design and as-built configuration.

Req. F20.1- FCF shall provide diagnostics commonly needed by Fluid Physics experiments. Compliance shall be shown by analysis of the FCF design (indicating appropriate "hooks and scars") and test of each diagnostic prior to its launch.

2.3.4 - Analog Measurements

Req. F21.1 - FCF shall be capable of accommodating acquisition and storage of temperature data from a variety of transducers at various ranges, precisions, and data rates per the estimates in figures F21a, F21b, and F21c. Compliance shall be shown by analysis of the design and as-built configuration combined with performance tests.

Req. F21.2 - FCF shall identify temperature measurement instruments or techniques appropriate to the needs of the basis experiments (as implied by figures F21a, F21b, and F21c) and verify their performance in FCF systems. The transducer specifications, test information and, samples shall be made available to PI hardware developers. Compliance shall be shown by analysis of the design and as-built configuration combined with performance tests.

Req. F22.1 - FCF shall be capable of accommodating acquisition and storage of pressure data at various ranges, precisions, and data rates per the estimates in figures F22a and F22b. Compliance shall be shown by analysis of the design and as-built configuration combined with performance tests.

Req. F22.2 - FCF shall identify pressure measurement instruments or techniques appropriate to the needs of the basis experiments (as implied by figures F22a and F22b) and verify their performance in FCF systems. The transducer specifications, test information, and samples shall be made available to PI hardware developers. Compliance shall be shown by analysis of the design and as-built configuration combined with performance tests.

Req. F23.1 - FCF shall be capable of accommodating acquisition and storage of force data at various ranges, precisions, and data rates per the estimates in figures F23a and F23b. Compliance shall be shown by analysis of the design and as-built configuration combined with performance tests.

Req. F23.2 - FCF shall identify force measurement instruments or techniques appropriate to the needs of the basis experiments (as implied by figures F23a and F23b) and verify their performance in FCF systems. The transducer specifications, test information, and samples shall be made available to PI hardware developers. Compliance shall be shown by analysis of the design and as-built configuration combined with performance tests.

Req. F24.1 - FCF shall be capable of accommodating acquisition and storage of voltage data at various ranges, precisions, and data rates per the estimates in figures F24a and F24b. Compliance shall be shown by analysis of the design and as-built configuration combined with performance tests.

Req. F24.2 - FCF shall identify voltage measurement instruments or techniques appropriate to the needs of the basis experiments (as implied by figures F24a and F24b) and verify their performance in FCF systems. The transducer specifications, test information, and samples shall be made available to PI hardware developers. Compliance shall be shown by analysis of the design and as-built configuration combined with performance tests.

2.4 - EXPERIMENT DATA ACQUISITION AND CONTROL

2.4.1 - Data Acquisition

Req. F25 - FCF shall be capable of simultaneously sampling multiple channels of analog signals originating in PI hardware with sampling rates, as required to accommodate the basis experiments. Compliance shall be shown by analysis of the design and as-built configuration combined with performance tests.

Req. F26 - FCF shall be capable of simultaneously sampling multiple channels of digital signals originating in PI hardware, as required to accommodate the basis experiments. Compliance shall be shown by analysis of the design and as-built configuration combined with performance tests.

2.4.2 - Data Recording

Req. F27.1 - FCF shall provide non-volatile storage for experiment-specific non-image data (e.g., transducer readings) as required by the basis experiments. Compliance shall be shown by analysis of the design and as-built configuration combined with performance tests.

Req. F28.1 - FCF shall provide the capability to time tag all data, including video data relative to an ISS provided timing signal. The time tag shall be of equivalent accuracy and precision to the ISS on-board timing signal or as required by the basis experiments, whichever is less stringent. Compliance shall be shown by analysis of the design and as-built configuration combined with performance tests.

Req. F28.2 - FCF shall provide the capability to time tag all data relative to an ISS provided clock signal and an FCF provided internal clock signal. The accuracy and precision of the time tag shall be approximately 0.1s and 0.01s, respectively.

2.4.3 - Experiment Control

Req. F29 - FCF shall provide multiple channels of analog output. These shall be capable of waveform generation as well as producing point voltage values. The quantity of channels, their accuracy, and their precision shall be adequate to control the basis experiments. Compliance shall be shown by analysis of the design and as-built configuration combined with performance tests.

Req. F30 - The facility shall provide internal and external triggering capability to enable the individual experiments to trigger and correlate various events. Compliance shall be shown by analysis of the design and as-built configuration.

Req. F31 - FCF shall be capable of simultaneously outputting multiple channels of digital signals to PI hardware, as required to accommodate the basis experiments. Compliance shall be shown by analysis of the design and as-built configuration.

Req. F32 - FCF shall be able to accommodate experiment specific computer cards (minimum of two card slots) in an FCF computer near the Fluid Physics work volume and to accommodate PI software for experiment control and analysis (i.e., accommodate PI hardware and software). Compliance shall be shown by analysis of the design and as-built configuration.

Req. F33 - The FCF shall provide a high performance computing and data-handling capability for onboard image and data processing to enable telescience adaptation of science procedures which actually depend on more data than is feasible to down/up link with the ISS limited. Compliance shall be shown by analysis of the design and as-built configuration.

Appendix D - Summary Table of Science Requirements, Desired Capabilities, and Compliance Verifications

3.0 - COMBUSTION REQUIREMENTS ENVELOPES

3.2 - EXPERIMENT OPERATING CONDITIONS

3.2.1 - Physical Considerations

Req. C1 - The FCF shall provide a combustion chamber with adequate volume and dimensions to accommodate the test sections of basis experiments c1 through c11. Requirements are shown in Figures C1a-b. Compliance shall be verified by analysis and conceptual layouts that show that the FCF, augmented by PI-specific hardware, meets the requirement.

Req. C2 - The FCF shall provide a capability for storage, distribution and mixing of fuels and oxidizer. Fuels can be gaseous (e.g., hydrocarbons, alkenes and selected aromatics); liquid (e.g., alcohols and alkanes); or solid fuels (e.g., polymers, wood, cloth, and selected metals).

The FCF shall also provide power and controls for igniting fuel/oxidizer mixtures using experiment provided igniter mechanisms. Typical ignition mechanisms include hot wires and surfaces, sparks, and lasers. Compliance shall be verified by conceptual layouts and analysis that show that the FCF, augmented by PI-specific hardware, meets the requirement.

Req. C3 - The FCF shall provide an environment which minimizes the "quasi-steady state" accelerations, vibratory disturbances, and transient impulses. Requirements are shown in Figure C3. Compliance shall be verified by analysis that shows that the FCF, augmented by other support hardware, meets the requirement.

3.2.2 - Initial Thermodynamic State

Req. C4 - The FCF shall provide pressure containment and control for initial gas pressures in the range of 0.02 to 3 atmosphere. The FCF shall provide containment and control for the pressure to remain constant within 5% throughout the test time. It shall provide containment for pressure increases to 9 atmosphere (absolute). The FCF shall provide control for initial gas temperatures of 268 to 320 K. Condensed phase fuel temperatures shall be controllable to ±1 K in the range 268 to 315 K at the start of testing. Compliance shall be verified by test and analysis that show that the FCF, augmented by PI-specific hardware, meets the requirement.

Req. C5 - The FCF shall provide oxidizer, which will generally be a mixture of oxygen and one or more diluents. Oxygen concentration in this mixture will vary over the range of 0 to 70%. Selected requirements are shown in Figures C5a-b.

The FCF shall also have the capability to dispense pre-mixed oxidizer/fuel mixtures from gas bottles into the combustion chamber. Compliance shall be verified by test and analysis that show that the FCF, augmented by PI-specific hardware, meets the requirement.

3.2.3 - Initial Fluid Dynamics State

Req. C6 - The FCF shall provide controlled flow of fuel over the volume flow rate range of 0 to 30 cc/sec under standard conditions (i.e., scc/sec) and controlled flow of oxidizer over the volume flow rate range of 0 to 4,000 scc/sec with an accuracy of 10% and a stability of 5% of the set point.. Compliance shall be verified by test and analysis that show that the FCF, augmented by PI-specific hardware, meets the requirement.

3.2.4 - Test Matrix

Req. C7 - The FCF shall provide all necessary support (e.g., data storage, fuel, oxidizer, and diluent storage and distribution, combustion product collection and disposal) to accomplish experiments having ranges of duration and repetition represented by the basis experiments described in this document. Requirements are shown in Figure C7. Compliance shall be verified by analysis that shows that the FCF, augmented by PI-specific hardware, meets the requirement.

3.3 - EXPERIMENTAL MEASUREMENTS

3.3.1 - Evolution of the Combustion Region

Req. C8 - The FCF shall provide imaging systems, illumination sources, power, control and data acquisition capabilities for imaging in the visible spectrum (400-700 nm). The imaging systems shall accommodate the envelopes of parameters defined for the basis experiments. Framing rates to 100/sec are required. Requirements are shown in Figure C8a-c. When the visible sensor is used primarily as a temperature, velocity, or soot measurement sensor, additional requirements apply (see Requirements C12, Temperature Field Measurements, C14, Chemical Composition and Soot Measurements, and C17, Full Field Velocity Imaging). Compliance shall be verified by test and analysis that show that the FCF, augmented by PI-specific hardware, meets the requirement.

Req. C9 - The FCF shall provide imaging systems, power, control and data acquisition capabilities to image flames and surfaces in the infrared spectrum in the wavelength range of 1,000 to 5,000 nm and 8,000 to 14,000 nm.

Framing rates to 60/sec are required. Requirements are shown in Figures C9a-c. When the infrared imager is used primarily as a temperature sensor, additional requirements apply (see Requirements C11 and C12, Temperature Measurements). Compliance shall be verified by test and analysis that show that the FCF, augmented by PI-specific hardware, meets the requirement.

Req. C10 - The FCF shall provide imaging systems, power, control and data acquisition capabilities for imaging in the ultraviolet spectrum (nominally 250 to 400 nm). Framing rates to 100/sec are required. Requirements are shown in Figures C10a-c. Compliance shall be verified by test and analysis that show that the FCF, augmented by PI-specific hardware, meets the requirement.

3.3.2 - Evolution of the Thermodynamic State

Req. C11 - FCF shall provide power, control and data acquisition capabilities for making multi-point temperature measurements in the gaseous and condensed phases during the course of experiment operations. Up to 12 temperature measurements in the gas phase and up to 20 temperature measurements in the condensed phase are required. Measurements shall be sampled at selectable rates to 1,000 samples per second in the gas phase and to 30 samples per second in the condensed phase. The temperatures in the gas phase range from 280 to 2,000 K and, in the condensed phase, range from 200 to 1,100 K. Requirements are shown in Figures C11a-d. Compliance shall be verified by test and analysis that show that the FCF, augmented by PI-specific hardware, meets the requirement.

Req. C12 - The FCF shall provide power, control and data acquisition capabilities for measuring temperature fields in the gaseous and condensed phases during the combustion experiment operations. Temperature fields may span the range 280 to 2,000 K in the gas phase and 260 to 1300 K in the condensed phase. Sample rate shall be selectable to at least 60 samples/second. Requirements are shown in Figures C12a-f. Compliance shall be verified by test and analysis that show that the FCF, augmented by PI-specific hardware, meets the requirement.

Req. C13 - The FCF shall provide power, control and data acquisition capabilities for measuring pressure of the test section during the course of experiment operations. Pressures may span the range 0 to 10 atm. The FCF shall provide static (less than or equal to 30 Hz) pressure transducers that meet the range and accuracy of the basis experiments. Requirements are shown in Figures C13a-b. Compliance shall be verified by test and analysis that show that the FCF, augmented by PI-specific hardware, meets the requirement.

Req. C14 - The FCF shall provide sensor systems, power, control and data acquisition capabilities for measuring chemical composition by gas sampling and gas analysis. The components to be measured are hydrogen, methane, propane, oxygen, nitrogen, carbon monoxide, carbon dioxide, sulfur hexafluoride, and water. The range of required measurements shall be 0.1 to 100% by volume with an accuracy of 2% of reading.

The FCF shall provide power, control and data acquisition capabilities for measuring soot volume fraction, soot temperature, and for collecting soot particles in the test section during a combustion experiment. Requirements are shown in Figures C14a-c. Compliance shall be verified by test and analysis that show that the FCF, augmented by PI-specific hardware, meets the requirement.

Req. C15 - The FCF shall provide power, control and data acquisition capabilities for measuring radiated energy in the spectral range 200 to 40,000 nm during the combustion experiment. Requirements are shown in Figure C15. Compliance shall be verified by test and analysis that show that the FCF, augmented by PI-specific hardware, meets the requirement.

3.3.3 - Evolution of the Fluid Dynamics

Req. C16 - The FCF shall provide power, control and data acquisition capabilities to measure gas velocity in the test section over the range of 0.5 to 5,000 cm/sec. Measurements shall be made at selected locations (1 to 20) in the test section and sampled at rates from 2 to 1,000 samples/second. The FCF shall accommodate the exhaust of seeding particles. Requirements are shown in Figures C16a-b. Compliance shall be verified by test and analysis that show that the FCF, augmented by PI-specific hardware, meets the requirement.

Req. C17 - The FCF shall provide power, control and data acquisition capabilities for full field imaging of velocities in the gas and liquid phases. Measurements shall encompass the required fields of views and be imaged at rates of 30 to 60/ second. The FCF shall accommodate the exhaust of seeding particles. Field of view requirements are shown in Figure C17. Compliance shall be verified by test and analysis that show that the FCF, augmented by PI-specific hardware, meets the requirement.

Req. C18 - The FCF shall provide a capability to (typically) monitor residual acceleration and g-jitter over a dynamic range of 10^{-6} to 10^{-2} g/g_0 within the Combustion Facility rack. Specific requirements on frequency and levels will be called out in experiment-specific science requirements, but are expected to fall within the standard parameter range of the Space Acceleration Measurement System (SAMS) accelerometer system. Requirements are shown in Figures C18a-b. Compliance shall be verified by analysis that shows that the FCF, augmented by supporting hardware systems, meets the requirement.

3.4 - Data Management

Req. C19 - The FCF shall provide a capability to time tag all data streams (including video data). A common clock (correlated to International Space Station events) shall be referenced and digital tags shall permit resolution to 1 second for external events and 0.001 second for experiment events. Compliance shall be verified by test and analysis that show that the FCF, augmented by PI-specific hardware, meets the requirement.

Req. C20 - The FCF shall provide, simultaneously, up to eight field measurements and up to 35 single sensor measurements. The FCF shall simultaneously provide the required controls and measurements to operate the PI-specific hardware (required by the science requirements) inside and outside the chamber. Compliance shall be verified by test and analysis that show that the FCF, augmented by PI-specific hardware, meets the requirement.

4.0 - OPERATIONS ENVELOPE REQUIREMENTS

4.2 - EXPERIMENT DEVELOPMENT

Req. O1 - The FCF mission planning and utilization organization shall provide and schedule PI team access to FCF simulators for verification of PI hardware and operations procedures. Compliance shall be shown by documentation of required plans and procedures accompanied by supporting analysis and logical arguments.

Req. O2 - The FCF mission planning and utilization organization shall schedule verification activities so that each PI team has time to simulate more than one mission timeline sequence in the flight like configuration. Compliance shall be shown by documentation of required plans and procedures accompanied by supporting analysis and logical arguments.

Req. O3 - Calibration, verification, and functional test data shall be made available within two weeks to the PI team at completion of each test cycle and shall remain available for at least 90 days following completion of the verification test activities. Compliance shall be shown by documentation of required plans and procedures accompanied by supporting analysis and logical arguments.

Req. O4 - Functional performance of facility-provided measurement instrumentation as-integrated with PI team provided hardware shall, typically, be verified in-situ and be traceable to certified reference standards (e.g., temperature, pressure, illumination intensity). As an aspect of this requirement, FCF shall have means to periodically re-verify the functional performance of instruments that will remain on-orbit. Compliance shall be shown by documentation of required plans and procedures accompanied by supporting analysis and logical arguments.

4.3 - FLIGHT OPERATIONS

Req. O5 - FCF shall routinely monitor primary environmental parameters (i.e., temperature, pressure, humidity, and acceleration) within each FCF rack and provide that data to the PI teams before, during, and after the mission – when stated in approved Science Requirements or negotiated FCF operating agreements. Compliance shall be shown by documentation of required plans and procedures accompanied by supporting analysis and logical arguments.

Req. O6 - FCF shall routinely provide ancillary ISS data (as available from ISS) to the PI teams including information on crew activities, maneuvers, docking, altitude, attitude, etceteras as stated in approved Science Requirements. Compliance shall be shown by documentation of required plans and procedures accompanied by supporting analysis and logical arguments.

Req. O7 - FCF shall provide near-real-time data and at least two imaging channels of downlink and near-real-time command up-link, as specified in the approved SRD, to permit true telescience. Compliance shall be shown by documentation of required plans and procedures accompanied by supporting analysis and logical arguments.

Req. O8 - FCF shall provide reliable capabilities for recording and protecting science data on-orbit. This capability shall include: Adequate computer memory or other storage media to record all required data from one data point of each active experiment in a time tagged format. Ability to downlink recorded data, limited only by ISS communications bandwidth restrictions on FCF. Clear identification of data existing only on-orbit to assure that no data is accidentally "erased". Ability to transfer data to portable media for return to earth via the Space Shuttle or other transport device. Compliance shall be shown by documentation of required plans and procedures accompanied by supporting analysis and logical arguments.

Req. O9 - FCF shall monitor all essential ISS, FCF, and PI hardware parameters to identify off nominal conditions, communicate such conditions to affected parties, and allow initiation of timely corrective actions that protect the science objectives of operating experiments. In particular, the "quality" of data downlink and command up-link shall be frequently verified. Compliance shall be shown by documentation of required plans and procedures accompanied by supporting analysis and logical arguments.

Req. O10 - FCF shall provide both local and remotely located PIs with any custom hardware and software required to display sequential data from FCF sensors (e.g., time, temperature) in tabular or graphical form, and to perform simple statistical transformations on that data (e.g., curve fitting). Compliance shall be shown by documentation of required plans and procedures accompanied by supporting analysis and logical arguments.

Req. O11 - FCF shall provide both local and remotely located PIs with any custom hardware and software required to display images acquired by FCF. Compliance shall be shown by documentation of required plans and procedures accompanied by supporting analysis and logical arguments.

4.4 - POST-FLIGHT OPERATIONS

Req. O12 - FCF shall store on-orbit and subsequently return to the PI team all existing PI-team-provided, experiment-specific equipment, samples, and data utilized or produced during operation of the experiment, per formal pre-flight agreements between FCF and the PI team. Compliance shall be shown by documentation of required plans and procedures accompanied by supporting analysis and logical arguments.

Req. O13 - FCF shall make available to the PI all relevant data generated during flight operations. Compliance shall be shown by documentation of required plans and procedures.

Req. O14 - FCF shall identify and fill (as possible) gaps in the negotiated data due to communications outages or equipment failures. Compliance shall be shown by documentation of required plans and procedures accompanied by supporting analysis and logical arguments.

Req. O15 - FCF shall provide access to all negotiated data for at least 90 days following completion of on-orbit operations. Compliance shall be shown by documentation of required plans and procedures accompanied by supporting analysis and logical arguments.

Req. O16 - FCF shall deliver all negotiated data in hard copied format within 60 days following completion of on-orbit operations or within 60 days of return from orbit for data that must be physically transferred to Earth, and FCF shall have one preferred medium and data format(s) for delivery of hard copies. Compliance shall be shown by documentation of required plans and procedures accompanied by supporting analysis and logical arguments.

Appendix D - Summary Table of Science Requirements, Desired Capabilities, and Compliance Verifications

D.2 DESIRED CAPABILITIES AND COMPLIANCE CRITERIA

1.0 - FCF LEVEL 1 REQUIREMENTS

2.0 - FLUIDS REQUIREMENTS ENVELOPE

2.2 - EXPERIMENT OPERATING ENVIRONMENT

2.2.1 - Physical Environment

Des. DF1.1 - It is desired that FCF provide a Fluid Physics work volume that will accommodate 100% of the Fluid Physics Basis Experiments.

Des. DF1.2 - It is desired that the facility be able to concurrently accommodate at least 2 experiments within the work volume, each having its own diagnostic system. Compliance shall be demonstrated by analysis and conceptual layouts that show that the FCF provides the desired capability.

Des. DF1.3 - It is desired that FCF provide multiple options for mounting PI hardware within the work volume and provide procedures that allow the positions of critical PI hardware elements to be established. Compliance shall be demonstrated by analysis and conceptual layouts that show that the FCF provides the desired capability.

Des. DF1.4 - It is desired that FCF provide at least one level of containment for laser light (or other bright lights) that might pose a crew health hazard during experiment operation. Additional levels of containment, if required, may be provided by PI hardware. Compliance shall be demonstrated by analysis and conceptual layouts that show that the FCF provides the desired capability.

Des. DF1.5 - It is desired that FCF provide a temporary level of containment for fluids originating in PI hardware during experiment set up, reconfiguration, and test cell change-out. Compliance shall be demonstrated by analysis and conceptual layouts that show that the FCF provides the desired capability.

Des. DF1.6 - It is desired that FCF be capable of providing at least one level of containment for particulates larger than 1.0 mm originating from PI hardware during experiment operation. Compliance shall be demonstrated by analysis and conceptual layouts that show that the FCF provides the desired capability.

Des. DF1.7 - It is desired that FCF provide capabilities for gas sampling of and atmosphere circulation within the work volume that are similar to and compatible with analysis and filtration systems in the Combustion Element of

FCF. Compliance shall be demonstrated by analysis and conceptual layouts that show that the FCF provides the desired capability.

Des. DF4.1 - It is desired that the facility measure the relative humidity, accurate to within +/- 10%, in the work volume. Compliance shall be demonstrated by analysis and conceptual layouts that show that the FCF provides the desired capability.

2.2.2 - Resources

Des. DF7.1 - It is desired that FCF provide the ability to implement a “sleep” mode on PI-provided circuit cards (particularly those PI-provided cards used in facility computers) to selectively conserve power resources during low levels of use. Compliance shall be demonstrated by analysis and conceptual layouts that show that the FCF provides the desired capability.

Des. DF8.1 - It is highly desirable that the standard deviation from mean intensity of the uniform background lighting be less than 0.2 percent (9 bit). Compliance shall be demonstrated by analysis and conceptual layouts that show that the FCF provides the desired capability.

Des. DF8.2 - It is desired that the illumination not limit the optical resolution and not cause ringing in the image (i.e., the light should be, at most, partially coherent. Compliance shall be demonstrated by analysis and conceptual layouts that show that the FCF provides the desired capability.

Des. DF9.1 - It is desired that FCF be capable of maintaining at least 4 lasers on orbit and have additional laser heads available for modifications and change-out. It is presumed that solid state lasers will be used whenever possible. Compliance shall be demonstrated by analysis and conceptual layouts that show that the FCF provides the desired capability.

Des. DF9.2 - It is desired that laser heads be considered distinct and detachable from drivers for flexibility. Compliance shall be demonstrated by analysis and conceptual layouts that show that the FCF provides the desired capability

Appendix D - Summary Table of Science Requirements, Desired Capabilities, and Compliance Verifications

2.3 - EXPERIMENT MEASUREMENT CAPABILITIES

2.3.2 - Optical Interfaces

Des. DF14.1 - It is desirable to have at least two viewing directions be accessible with zoom capability. Compliance shall be demonstrated by analysis and conceptual layouts that show that the FCF provides the desired capability.

Des. DF14.2 - It is desirable to have images of directly opposite views; e.g., front and rear view of an object should be accessible. Compliance shall be demonstrated by analysis and conceptual layouts that show that the FCF provides the desired capability.

Des. DF14.3 - It is desirable to have ability to image two orthogonal views side by side with the same camera. Compliance shall be demonstrated by analysis and conceptual layouts that show that the FCF provides the desired capability.

2.3.3 Optical Measurements

Des. DF18.1 - It is desired that the facility not preclude higher camera frame rates (e.g., 2000 fps). Compliance shall be demonstrated by analysis and conceptual layouts that show that the FCF provides the desired capability.

Des. DF 19.1 Continuous communication between the experiment ground operations team and the facility is highly desirable. Compliance shall be demonstrated by analysis and conceptual layouts that show that the FCF provides the desired capability.

Des. DF20 - It is desired that FCF provide the following optical diagnostic capabilities as FCF supplied hardware and software per the recommendations in table DF20:

DF20.1 General Video Imaging

DF20.2 Video Microscopy

DF20.3 Static Light Scattering

DF20.4 Dynamic Light Scattering

DF20.5 Shadowgraphy

DF20.5 Particle Image Velocimetry

DF20.6 Shearing Interferometry

DF20.7 Surface Profilometry

Compliance for all desired capabilities in DF 20 shall be demonstrated by analysis and conceptual layouts that show that the FCF provides the desired capability.

2.4 - EXPERIMENT DATA MANAGEMENT

2.4.1 - Data Acquisition

Des. DF25.1 - FCF should provide an analog to digital conversion system available for use by PI hardware. Compliance shall be demonstrated by analysis and conceptual layouts that show that the FCF provides the desired capability.

2.4.2 - Data Storage

Des. DF27.1 - It is desired that all data should be recorded using standard commercial formats that can be easily accessed by PI software. Compliance shall be demonstrated by analysis and conceptual layouts that show that the FCF provides the desired capability.

Des. DF27.2 - FCF should provide a minimum of 32 Mbyte of CPU bus speed storage (e.g., RAM) for experiment specific non-image data (e.g., transducer readings). Compliance shall be demonstrated by analysis and conceptual layouts that show that the FCF provides the desired capability.

Des. DF28.1 - It is desired that FCF provide capability to tag data at selectable precision and frequency. The precision/resolution on time tagging should be consistent with the data sampling rate used. Compliance shall be demonstrated by analysis and test.

2.4.3 - Experiment Control

Des. DF29.1 - It is desired that provisions be provided to increase the number of available D/A channels to 64 as demand increases. Compliance shall be demonstrated by analysis and conceptual layouts that show that the FCF provides the desired capability.

Des. DF29.2 - It is desired that a variety of wave forms be generated at selectable frequencies to 1 MHz and selectable amplitudes. Compliance shall be demonstrated by analysis and conceptual layouts that show that the FCF provides the desired capability.

Des. DF32 - It is recommended that an FCF Fluid Physics computer accommodate any or all of the following experiment-specific plug-in boards and associated PI software. The computer should be located near the dedicated Fluid Physics volume. The recommended single board capabilities include:

DF32.1 State-of-the-art frame grabber

DF32.2 Oscilloscope board

DF32.3 Lock-in amplifier

DF32.4 Time correlator (which support both digital and analog inputs)

DF32.5 Strain-gauge measurement

DF32.6 Thermocouple reference and amplifier

DF32.7 Frequency synthesizer.

Compliance for all desired capabilities in DF32 shall be demonstrated by analysis and conceptual layouts that show that the FCF provides the desired capability.

Des. DF32.8 - It is desired that FCF provide a custom electronics enclosure to provide accommodations for high-quality, low-noise measurement capabilities that may require careful protection from electromagnetic interference and temperature variations. Compliance shall be demonstrated by analysis and conceptual layouts that show that the FCF provides the desired capability.

3.0 - COMBUSTION REQUIREMENTS ENVELOPE

3.2 - EXPERIMENT OPERATING CONDITIONS

3.2.1 - Physical Considerations

Des. DC3.1 - It is desirable to have a quasi-steady acceleration level of 10^{-6} g/g_0 during conduct of experiments. Compliance shall be demonstrated by analysis and conceptual layouts that show that the FCF, augmented by PI-specific hardware, could provide the desired capability.

3.2.2 - Initial Thermodynamic State

Des. DC5.1 - It is desirable to have the ability to burn in a 100% oxygen environment. Compliance shall be demonstrated by analysis and conceptual layouts that show that the FCF, augmented by PI-specific hardware, could provide the desired capability.

Des. DC5.2 - It is desirable to have the ability to supply gas from more than one premixed bottle for a single test run. Compliance shall be demonstrated by analysis and conceptual layouts that show that the FCF, augmented by PI-specific hardware, could provide the desired capability.

3.2.3 Initial Fluid Dynamics State

Des. DC6.1 It is extremely desirable to have the capability to flow premixed fuel and oxidizer through the test section or PI-hardware in a controlled manner. Such experiments cannot utilize a recirculating flow. Overall (fuel and oxidizer) flow rates may range to 4,000 scc/sec. Compliance shall be demonstrated by analysis and conceptual layouts that show that the FCF, augmented by PI-specific hardware, could provide the desired capability.

3.3 - EXPERIMENTAL MEASUREMENTS

3.3.1 - Evolution of the Combustion Region

Des. DC8.1 - It is desirable to accommodate framing rates to 1000/sec for visible imaging. Compliance shall be demonstrated by analysis and conceptual layouts that show that the FCF, augmented by PI-specific hardware, could provide the desired capability.

Des. DC9.1 - It is desirable to accommodate framing rates to 1000/sec for IR imaging. Compliance shall be demonstrated by analysis and conceptual layouts that show that the FCF, augmented by PI-specific hardware, could provide the desired capability.

Des. DC10.1 - It is desirable to accommodate framing rates to 1000/sec for UV imaging. Compliance shall be demonstrated by analysis and conceptual layouts that show that the FCF, augmented by PI-specific hardware, could provide the desired capability.

3.3.2 - Evolution of the Thermodynamic State

Des. DC12.1 - It is desirable to accommodate sampling rates to 1000 samples/sec. Compliance shall be demonstrated by analysis and conceptual layouts that show that the FCF, augmented by PI-specific hardware, could provide the desired capability.

3.3.3 - Evolution of the Fluid Dynamics State

Des. DC17.1 - It is desirable to accommodate imaging rates to 1,000/second for image-based velocity measurement systems. Compliance shall be demonstrated by analysis and conceptual layouts that show that the FCF, augmented by PI-specific hardware, could provide the desired capability.

3.0 - OPERATIONS REQUIREMENTS ENVELOPE

3.4 - FLIGHT OPERATIONS

Des. DO1.1 - It is desirable that FCF shall provide video monitoring (standard video quality) of the crew to the PI team during PI hardware installation, selected operations, and servicing to enable real-time support by ground personnel and to provide a record of the on-orbit crew operations. Compliance shall be shown by documentation of required plans and procedures accompanied by supporting analysis and logical arguments.

Des. DO2.1 - It is desirable that FCF shall provide a video monitor for the crew that displays instructions, images, or other supporting data from ground personnel for the purpose of enhancing the efficiency of PI hardware setup, servicing, and operations interactions. Compliance shall be shown by documentation of required plans and procedures accompanied by supporting analysis and logical arguments.

Des. DO3.1 - It is desired that, during a mission, FCF PIs will often be located at their home institution and receive data from their experiment at their home institution. FCF should provide the equipment, software, and operational procedures to permit this. Provisions should be made to distribute all relevant data from a given experiment (including near-real-time science, environment, FCF status, and etceteras as negotiated) to at least 10 PI data terminals spread among at least 3 different PI sites that may be located anywhere. Compliance shall be shown by documentation of required plans and procedures accompanied by supporting analysis and logical arguments.

Appendix E - Data Tables for Fluids Experiments

Basis Experiment f1 - Thin Film Fluid Flows at Menisci

Imaging views & directions	A view of the meniscus near the wall including the wall and contact line (film thicknesses about 15 microns max).
Visual resolution	1 micron / 0.01 micron (0.01 micron is for static film profile measurement by interferometry).
Field of view	10 x 10 cm / 20 x 200 micron
Fluid & particle speed's	Axial velocities about 500 microns/sec; normal velocities about 1 microns/sec.
Framing rates	30 fps should be sufficient .
Exposure duration per image	Shutter speed of 0.5 milli-sec.
Image processing duration	Experiment duration.
Imaging equipment required	B/W digital imaging camera, possible IR camera, video microscope.
Optical diagnostics	General imaging; video microscopy, PIV (velocities); interferometry (film thickness).
Non-laser light sources	Diffuse white background lighting.
Laser light sources	TBD laser capability for PIV and interferometry.
Laser light mgmt	TBD light sheet and beam for interferometry and PIV.
Pres. measurement & cont'l	About 1 atm + 0.1 %.
Temp. measurement & cont'l	Fluid cell at a controllable temp.in the range of 20 to 25º; cont'd to +/- 0.1º.
G-jitter freq's	Below 10 Hz isolation.
DC g-levels	10-03 with align / 10-06 with no align.
Instrumentation/accuracies	Thermocouples are a possibility for calibration purposes; TBD accuracy.
Sampling rates/durations	No data yet.
Position field resolution	Measure film thicknesses from 0 to 15 microns with +/- 5% accuracy.
Temp. field resolution	Wall temps on the order of 20 to 25 deg-C; meas. to 0.001 deg-C; with a spatial resolution of +/- 5 microns.
Velocity field resolution	Axial velocities (up to about 500 microns/sec) measured to +/- 4 microns/sec; normal velocities (up to about 1 micron/sec) measured to +/- 0.1 microns/sec.
Concentration field resolution	N/A
Experiment duration	2 - 3 hours per test.
Number of tests	40 (5 different heat inputs, 2 reps, and 4 fluids).
Experiment matrix & ranges	Various TBD fill conditions and various TBD heat flux levels.
PI TC/equip dimensions	10 cm dia fluid cell; with fixed meniscus.
Special equipment required	Heated section for the meniscus; and a condensation section.
Particle sizes	5 - 20 microns
Fluids used	Pentane, methanol, acetone, f-113.
Crew operations & functions	test cell set up and changeout

Basis Experiment f2 - Contact Line Hydrodynamics

Imaging views & directions	Image surface shape near C/L; image entire free surface; and image entire cell; synched micro/macro viewing.
Visual resolution	Order of 2 to 3 microns (micro view).
Field of view	3 req'd: 2x2 mm within 5 microns of C/L; 1 to 5 cm gap view; and up to 15 cm entire cell.
Fluid & particle speed's	In range of 3 to 1000 microns/sec.
Framing rates	30 fps for transient data and 1 fps for steady state imaging.
Exposure duration per image	No data yet.
Image processing duration	at least 10 to 20 seconds of imaging per test (once s.s. has been reached).
Imaging equipment required	B/W digital imaging camera.
Optical diagnostics	B/W video, microscopy, PIV.
Non-laser light sources	Diffuse white background lighting.
Laser light sources	TBD laser to be used for PIV.
Laser light mgmt	Laser sheet of TBD characteristics.
Pres. measurement & cont'l	About 1 atm +/- 1 psia; no control.
Temp. measurement & cont'l	Range of 20 - 25º to +/- 3 deg-C; uniformity to +/- 2 deg-C for high visc. fld and +/- 0.1 deg-C for low visc. fld.
Humidity measurement & cont'l	Control to less than 6% rel. humidity.
G-jitter freq's	Amplitudes less than 0.0001 g/go for frequencies < 10 Hz.
DC g-levels	Less than 0.0001 g/go.
Instrumentation/accuracies	Temp. (+/- 0.05 deg-C); pressure, rod vel., fluid vol., temp. diff. across cell.
Sampling rates/durations	0.01 Hz for high viscosity fluid; and 0.3 Hz for low viscosity fluid; for exp. dur.
Position field resolution	Measure the height (thickness) of the fluid interface as function of position to +/- a few microns.
Temp. field resolution	N/A
Velocity field resolution	Measured to within 5 microns of C/L with accuracy of +/- 2% rod velocity.
Concentration field resolution	N/A
Experiment duration	10 to 20 min
Number of tests	About 250
Experiment matrix & ranges	Various rod velocities (9x up to 1000 microns/sec); gap/cell sizes (3x up to 5 cm), fluid choice (2x); and wetting characteristics (wetting, non-wetting).
PI TC/equip dimensions	About 15 x 30 cm (including volume necessary for rod translation).
Special equipment required	Nothing unusual.
Particle sizes	1 to 5 microns
Fluids used	Low (200 cSt) and high (60,000 cSt) viscosity PDMS.
Crew operations & functions	Test cell insertion and changeout.

Basis Experiment f3 –Rheology of Non-Newtonian Fluids

Imaging views & directions	View exponentially stretching fluid column; also focus on column behavior near contact areas.
Visual resolution	30 - 50 micron.
Field of view	At least half of column should be in view; alternate is to view 5 to 10 cm in from column contact points.
Fluid & particle speed's	Ranging from 0.004 to 150 cm/sec.
Framing rates	Ranging from 30 to 100 fps.
Exposure duration per image	Less than 0.001 sec (<1 milli-sec).
Image processing duration	1 - 150 sec.
Imaging equipment required	B/W digital imaging cameras.
Optical diagnostics	Particle imaging velocimetry; bi-refriginence diagnostics.
Non-laser light sources	None expected.
Laser light sources	Laser in the blue-green λ range, power density of about 0.2 mW/mm3; also ~ 10 mW unit for bi-refringence.
Laser light mgmt	< 300 microns sheet needed for imaging particle velocities.
Pres. measurement & cont'l	About 1 atm; no control .
Temp. measurement & cont'l	Measure & control in the range 20 to 26 deg-C with +/- 0.1 deg-C acc.; all tests with same temp., +/- 0.2 deg-C.
G-jitter freq's	< 0.018 g/go for freq's 0 to 5 Hz; < 0.03 g/go for freq's greater than 5 Hz.
DC g-levels	Less than 0.018 g/go.
Instrumentation/accuracies	1 to 10000 at +/- 1 dynes; and 100 to 1,000, 000 at +/- 100 dynes (force measurements); measure fluid temp.
Sampling rates/durations	100 Hz for exp. dur. for force meas.; and 4 Hz for temp. measurements.
Position field resolution	Measure column dia. to +/- 0.001 cm.
Temp. field resolution	N/A
Velocity field resolution	Velocities up to 150 cm/sec; 640x480 pixel array req'd for desired res. (about +/- 0.1 to 1.0 microns/sec).
Concentration field resolution	N/A
Experiment duration	About 60 min .
Number of tests	About 20.
Experiment matrix & ranges	Various fluids (2x) and various strain rates (about 8 for 1 fluid and 2 for the other).
PI TC/equip dimensions	2 ft dia x 4 ft long.
Special equipment required	Bi-refringence diag., force trans.
Particle sizes	50-microns sized silver-coated glass spheres at about 3400 per ml of fluid.
Fluids used	Monodisperse polystyrene in oligomeric polystyrene oil misture (non-Newtonian); and oligomeric polystyrene oil (Newtonian).
Crew operations & functions	Test cell insertion and changeout.

Basis Experiment f4 – Dynamics of Hard Sphere Colloids

Imaging views & directions	Bragg scattering images as well as color images of entire cell.
Visual resolution	About 10 to 50 microns.
Field of view	10 x 20 mm.
Fluid & particle speed's	N/A
Framing rates	Ranges from 2 fps to 10 sec per frame.
Exposure duration per image	No data yet.
Image processing duration	About 30 sec; taken periodically about every 30 minutes.
Imaging equipment required	B/W and color digital cameras.
Optical diagnostics	Sm. and lg. angle light scattering; Bragg scattering; and general color imaging.
Non-laser light sources	Kohler illumination (collimated white light) required.
Laser light sources	Laser required for various light scattering diagnostics; λ = 532 nm; power > 30 mW; +/- 0.1% stability.
Laser light mgmt	Variable beam diameter from 100 microns to 10 mm.
Pres. measurement & cont'l	About 1 atm; no control necessary.
Temp. measurement & cont'l	Ambient temperatures; no control necessary .
G-jitter freq's	No data yet.
DC g-levels	Less than 0.001 g/go .
Instrumentation/accuracies	DLS detectors; measuring rotation (1rps) and oscillation rates (< 50 Hz max); temp. recorded +/- 0.1 deg-C.
Sampling rates/durations	Light scattering data from 30 Hz to seconds per image.
Temp. field resolution	N/A
Velocity field resolution	N/A
Concentration field resolution	N/A
Experiment duration	4 hours to 10 days (avg 24 hours).
Number of tests	About 30.
Experiment matrix & ranges	Control parameters are particle concentrations ranging from 0.47 to 0.64; and particle dia (0.6 to 1 micron).
PI TC/equip dimensions	20 (dia) x 10 mm / sample volume is 4 ml; accommodate slight Δ's in volume; should also accommodate rotation at 1 rps and oscillation from 0.1 to 50 Hz.
Special equipment required	Equipment necessary to rotate and oscillate samples; corellator boards and DLS detectors.
Particle sizes	PMMA particles, 0.6 to 1.0 microns (single size in samples; but ranges over samples).
Fluids used	PMMA with decalin, tetralin.
Crew operations & functions	Test cell insertion and changeout.

Basis Experiment f5 – Colloids Physics

Imaging views & directions	Bragg scattering images as well as color images of entire cell.
Visual resolution	About 25 to 50 microns.
Field of view	10 x 20 mm
Fluid & particle speed's	N/A
Framing rates	Single frame video or still camera; images once per hour.
Exposure duration per image	No data yet.
Image processing duration	About 30 sec; every 30 min .
Imaging equipment required	B/W and color digital cameras.
Optical diagnostics	Sm. and lg. angle light scattering; Bragg scattering; and general color imaging.
Non-laser light sources	Kohler illumination (collimated white light) required.
Laser light sources	Laser required for various light scattering diagnostics; λ = 532 nm; power > 30 mW; +/- 0.1% stability.
Laser light mgmt	Var. beam dia. from 0.1 to 10 mm.
Pres. measurement & cont'l	About 1 atm; no control necessary.
Temp. measurement & cont'l	Ambient temperatures; no control necessary; vary < +/- 5 deg-C for missions and < +/- 0.5 deg-C for DLS.
G-jitter freq's	No data yet.
DC g-levels	Less than 0.001 g/go.
Instrumentation/accuracies	DLS detectors; measuring rotation (1rps) and oscillation rates (2 to 15 Hz); temp. recorded +/- 0.1 deg-C.
Sampling rates/durations	Temp. measurements every 10 min; light scattering data at 1 Hz.
Temp. field resolution	N/A
Velocity field resolution	N/A
Concentration field resolution	N/A
Experiment duration	1 hour to 5 days (avg 24 hours).
Number of tests	About 25 – 100.
Experiment matrix & ranges	Various fluid/particle combinations; various particle concentrations; periodically imaged and diagnosed.
PI TC/equip dimensions	20 (dia) x 10 mm / sample volume is 4 ml; accommodate slight Δ's in volume; should also accommodate rotation at 1 rps and oscillation from up 15 Hz.
Special equipment required	Equipment necessary to rotate and oscillate samples; corellator boards and DLS detectors.
Particle sizes	Ranging from 10 to 5000 nm.
Fluids used	Decalin, tetralin fluids; polystyrene, silica and gold particles (fractal agg.); PMMA, PMMA-silica, and PMMA-metal combos for binary exp's.
Crew operations & functions	Test cell insertion and changeout.

Basis Experiment f6 – Studies in Electrohydrodynamics

Imaging views & directions	View of the entire cylinder; two orthogoal views required.
Visual resolution	About 100 microns for overall view.
Field of view	5 to 10 cm for overall cylinder; about 1 mm for detailed pinchoff phenomena.
Fluid & particle speed's	Up to about 1 cm/sec.
Framing rates	Generally about 30 fps; 100 - 500 fps for pinchoff phenomena.
Exposure duration per image	No data yet.
Image processing duration	20 min at 30 fps; and 10 sec at higher frame rates.
Imaging equipment required	B/W digital imaging camera.
Optical diagnostics	General video for overall views; some views with magnification.
Non-laser light sources	Diffuse white background lighting.
Laser light sources	None anticipated.
Laser light mgmt	N/A
Pres. measurement & cont'l	About 1 atm; no control.
Temp. measurement & cont'l	20 - 25 deg C controlled +/- 0.5 deg-C for each test.
Voltage meas. & cont'l	0 to 20,000 volts controlled to +/- 5 % / (0 - 5 kV/cm and 0 - 500 Hz AC).
G-jitter freq's	No data yet.
DC g-levels	< 0.00001 g/go for 45 min; < 0.0001 g/go for 60 min.
Instrumentation/accuracies	Measure temperatures to +/- 0.1 deg-C accuracy; measure voltages and currents to +/- 1% accuracy.
Sampling rates/durations	Temperatures about 1 Hz; voltages and currents about 10 Hz .
Position field resolution	Accurately measure cylinder diameter to +/- 1% via imaging.
Temp. field resolution	N/A
Velocity field resolution	Measured to an accuracy of +/- 5 % via general imaging.
Concentration field resolution	N/A
Experiment duration	15 - 30 min.
Number of tests	About 80.
Experiment matrix & ranges	Parameters include: fluid combos; voltage levels/types; L/D ratio; voltage ramp rates.
PI TC/equip dimensions	Liquid columns are 5 mm in dia. with L/D's from 3 to 10; overall test container about 20 x 40 x 25 cm.
Special equipment required	High voltage power source; capability to measure very sm. currents
Particle sizes	N/A
Fluids used	Liquids: mineral oil, castor oil, silicone oil, water; gases: SF6.
Crew operations & functions	Test cell insertion and changeout.

Basis Experiment f7 – Nucleation and Growth of Microporous Crystals

Imaging views & directions	General viewing of crystals at different stages of growth in the cells.
Visual resolution	1 - 5000 nm (applicable for LLS capability); 10 microns for visual imaging (i.e., non-microscopic).
Field of view	1 - 10 cm depending upon ultimate cell size and crystal size at the time.
Fluid & particle speed's	N/A
Framing rates	30 fps.
Exposure duration per image	Shutter speed of 0.5 milli-sec.
Image processing duration	1 to 2 minutes per imaging period.
Imaging equipment required	B/W digital imaging camera.
Optical diagnostics	General imaging with video; some magnification may be required; dynamic light scattering.
Non-laser light sources	Diffuse white background lighting.
Laser light sources	laser light required for dynamic light scattering; diode with λ = 675 nm and 3 mW has been used on ground.
Laser light mgmt	Optics necessary to perform DLS.
Pres. measurement & cont'l	Ambient 1 atm; no measurement nor control necessary.
Temp. measurement & cont'l	20 to 25 deg-C cont'd to +/- 1 deg-C.
G-jitter freq's	No data yet.
DC g-levels	Less than 0.0001 g/go.
Instrumentation/accuracies	Periodic temperature measurement.
Sampling rates/durations	Temperature measurement at 0.01 Hz; DLS measurements about every hour for type A, every 30 min for type B, every 10 min for type C; diagnostics data take duration about 1 to 2 minutes; decreasing freq. with time.
Temp. field resolution	N/A
Velocity field resolution	N/A
Concentration field resolution	N/A
Experiment duration	All measurements complete for given sample at 10 days.
Number of tests	15 to 20 samples.
Experiment matrix & ranges	Only control parameter is initial concentration of reactant mixtures as contained in the various samples.
PI TC/equip dimensions	10 mm x 40 cm typical; each sample is about 100 ml.
Special equipment required	Must have separation and de-separation capability in cell; mixing capability; optical access for viewing and light scattering; APD's and corellators for DLS diagnostics.
Particle sizes	1 nm to about 3 mm (crystals sizes).
Fluids used	N-hexane, zinc nitrate, sodium hydroxide, phosphoric acid.
Crew operations & functions	Cell insertion, changeout, and perhaps mixing and sample preparation fctn's.

Basis Experiment f8 – Interactions of Bubbles and Drops

Imaging views & directions	General viewing of test cell with bubbles or drops; two orthogonal views required.
Visual resolution	1 - 5% of bubble diameters.
Field of view	general viewing of entire cell, about 5 x 10 cm; also closer views of 5 radii around drop/bubble required.
Fluid & particle speed's	1 - 60 cm/min / +/- 1 to 5% accuracy.
Framing rates	30 fps should be sufficient.
Exposure duration per image	No data yet.
Image processing duration	Experiment run duration.
Imaging equipment required	B/W digital imaging cameras.
Optical diagnostics	B/W video, PDI, WPI, tracking capability with camera.
Non-laser light sources	Diffuse white background lighting.
Laser light sources	TBD laser required for PIV and interferometry; sufficient power to support two orthogonal views .
Laser light mgmt	Sheet about 5 to 10 cm wide; beam for interferometry about 5 cm dia.
Pres. measurement & cont'l	1 atm +/- 5%; no control necessary; should be measured to +/- 1% .
Temp. measurement & cont'l	Cell temps ranging from -20 to 120 deg-C; uniform gradient; transverse variations < 0.1 deg-C; longitudinal gradient variations < +/- 1 deg-C/mm.
G-jitter freq's	Less than 0.00001 g/go for frequencies less than 0.01 Hz.
DC g-levels	Less than 0.00001 g/go
Instrumentation/accuracies	Various temperatures, thermocouples throughout cell (about 5 to 10).
Sampling rates/durations	1 Hz steady state / 10 Hz transient.
Temp. field resolution	Temperature fields to about 5 R around bubble, spatial resolution of 500 microns.
Velocity field resolution	Ranging from 0.01 to 1.0 cm/sec; measured to an accuracy of +/- 1%.
Concentration field resolution	N/A
Experiment duration	1 - 15 min with 2 hour equilibration
Number of tests	about 150.
Experiment matrix & ranges	Various temperature gradients; bubble sizes (1 to 20 mm); single or multiple deployments; various fluid combos.
PI TC/equip dimensions	5 x 5 x 10 cm; with heat controlled surfaces on the 5x5 cm faces; other surfaces transparent; min. heat loss.
Special equipment required	Bubble injection extraction devices.
Particle sizes	1 - 20 mm (bubble or droplet sizes); also particles of 10 to 20 microns required for external vel. field info.
Fluids used	Silicone oils, FC-75.
Crew operations & functions	Test cell insertion and changeout.

Basis Experiment f9 – Thermocapillary Migration of Bubbles and Drops

Imaging views & directions	Viewing bubbly suspension throughout cell; as well as close up views of bubbles near interface.
Visual resolution	1 - 5 % of bubble diameters.
Field of view	Three FOV's: overall view, ≈ 10x10 cm; for small clusters, ≈ 5 rad around interacting bubbles; and within 2 cm of coalescence at interface.
Fluid & particle speed's	1 - 60 cm/min / +/- 1 to 5% accuracy.
Framing rates	30 fps should be sufficient.
Exposure duration per image	No data yet.
Image processing duration	Experiment duration.
Imaging equipment required	B/W digital imaging camera.
Optical diagnostics	Video imaging, PDI & WPI (interfer.)
Non-laser light sources	Diffuse white background lighting.
Laser light sources	Laser req'd for WPI and PDI interfer.
Laser light mgmt	Interferometry beam ≈ 5 to 10 cm dia.
Pres. measurement & cont'l	About 1 atm; measured to +/- 1%.
Temp. measurement & cont'l	Cell temps ranging from -20 to 120 deg-C; uniform gradient; transverse variations < 0.1 deg-C; maximum temp. grad. expected 3 deg-C/mm
G-jitter freq's	Below 1 Hz isolation.
DC g-levels	< 0.001 g/go, vec. align. may be req'd.
Instrumentation/accuracies	Various temperatures, thermocouples throughout cell (about 5 to 10).
Sampling rates/durations	1 Hz steady state / 10 Hz transient.
Position field resolution	Bubbles dia. to within +/- 1 to 5% of dia.; phase segregation boundary and small bubble clusters tracked.
Temp. field resolution	Temp's ranging from –20 to 120 deg-C; internal grad. maintained to +/- 1 deg/mm; +/- 0.1 deg-C accuracy.
Velocity field resolution	Ranging from 0.01 to 1.0 cm/sec; measured to an accuracy of +/- 1%.
Concentration field resolution	N/A
Experiment duration	1 - 5 hours.
Number of tests	About 75.
Experiment matrix & ranges	Control parameters: fluid combos (≈ 3); vol. frac. of dispersed phase (1 to 10%); temp. grad.; and # of bubbles in small cluster exps.
PI TC/equip dimensions	10x15x1 cm; adjustable long dimen.
Special equipment required	Vector alignment may be necessary to study gravity induced motion.
Particle sizes	Bub. sizes: suspensions: 2 to 50 microns; interactions: 50 to 1000 mic.
Fluids used	Castrol/silicone oil, ethanol-diethalene-glycol/silicone oil, water/butyl benzoate; and air.
Crew operations & functions	Test cell insertion and changeout.

Basis Experiment f10 – Interfacial Transport and Miscellar Solubilization

Imaging views & directions	Viewing overall cell as well as interferometric images.
Visual resolution	1 to 5 microns for interferometry; and about 25 microns for overall.
Field of view	0.25 x 0.50 mm for interferometric views; and 0.25 x 4 cm for overall.
Fluid & particle speed's	N/A
Framing rates	300 fps for 5 sec for B/W for initial transients; afterwards 1 frame every 5 minutes; 1 color frame every 15 min.
Exposure duration per image	No data yet.
Image processing duration	Initial transients: 5 seconds; afterwards; 1 frame / 5 min (B/W) and 1 frame / 15 min (color).
Imaging equipment required	B/W digital camera for interferometry; and color digital camera for overall.
Optical diagnostics	Interferometry, and general color digital imaging.
Non-laser light sources	Diffuse white background lighting (prefer cold light sources).
Laser light sources	TBD laser required for interferometry.
Laser light mgmt	Beams required for interferometry (expanding from about 1 to 25 mm).
Pres. measurement & cont'l	About ambient ; no control necessary.
Temp. measurement & cont'l	In the range of 10 to 35 deg-C; controlled to +/- 0.01 deg-C.
G-jitter freq's	No data yet.
DC g-levels	Less than 0.001 req'd; less than 0.0001 desired.
Instrumentation/accuracies	Various temperatures measurements in cell; about 5 measurements in total.
Sampling rates/durations	Temperature data about 1 Hz.
Temp. field resolution	N/A
Velocity field resolution	N/A
Concentration field resolution	Concentration information achieved via interferometry techniques.
Experiment duration	1 - 2 hours.
Number of tests	About 50 – 100.
Experiment matrix & ranges	Parameters include: absolute temperatures, variety of solutes, solute concentrations; variety of organic fluids.
PI TC/equip dimensions	Fluid cell about 4 x 3 x 1 cm fluid cell; overall apparatus about 15x15x15 cm.
Special equipment required	Filling on-orbit; or removable fluid separation mechanisms.
Particle sizes	N/A
Fluids used	Organic fluids: toluene, heptane, ethanol; solutes: methyl nicontonate.
Crew operations & functions	Test cell insertion and changeout.

Basis Experiment f11 – Thermocapillary and Double-Diffusive Phenomena

Imaging views & directions	Thermocapillary convection exp (TCCE); induced instabilities exp (IIE); double diffusion exp (DDE); velocity, temp. and concentration fields; two ortho. view req'd for some tests.
Visual resolution	≈ 100 microns for lg FOV; 10 microns for smaller FOV.
Field of view	Overall view 10 x 10 cm; more detailed viewing, 1 x 1 to 2 x 2 cm.
Fluid & particle speed's	0 - 20 cm/sec among all exps.
Framing rates	30 to 100 fps (TCCE & IIE); 1 to 30 fps (DDE).
Exposure duration per image	No data yet.
Image processing duration	10 sec at higher rates; 5 - 10 min at lower rates for all exps.
Imaging equipment required	B/W digital imaging camera, IR imaging in the 8 to 14 mm λ range.
Optical diagnostics	General B/W imaging, IR imaging, PIV, shadowgraph.
Non-laser light sources	Diffuse white background lighting.
Laser light sources	TBD lasers req'd for: PIV, surface profilometry, shadowgraphy, interferometry.
Laser light mgmt	Light sheets about 100 microns thick by 5 to 10 cm wide.
Pres. measurement & cont'l	Ambient pressures; no control req'd.
Temp. measurement & cont'l	TCCE & DDE: about 0 to 100 deg-C; cont'l to +/- 0.5 deg-C; meas. to +/- 0.1 deg-C; IIE: about 15 to 100 deg-C; cont'l to +/- 0.05 deg-C; meas. to +/- 0.01 deg-C.
G-jitter freq's	No data yet.
DC g-levels	< 0.0001 g/go for TCCE; < 0.000001 g/go for IIE (unless aligned); alignment required for DDE
Instrumentation/accuracies	Temperatures of heaters coolers; measured to +/- 0.1 deg-C (TCCE & DDE) or +/- 0.01 deg-C (IIE).
Sampling rates/durations	1 Hz at walls; 10 Hz internal to fluid.
Position field resolution	Surf. prof. acc. +/- 50 to 100 microns.
Temp. field resolution	+/- 0.1 deg-C for all exps.
Velocity field resolution	High vel's +/- 1%; +/- 10% low vel's.
Concentration field resolution	+/- 5% for DDE experiments.
Experiment duration	1 - 2 hours.
Number of tests	About 150.
Experiment matrix & ranges	Parameters: cell size/shapes; aspect ratio; temp. grad.; conc. grad.; fluids.
PI TC/equip dimensions	On-orbit filling for 2 exps; transparent and temp. cont'ld walls; TCCE: 10x10x10 cm; IIE: ≈ 5x20 cm; DDE: ≈ 25 cm with aspect ratio from 0.1 to 10.
Special equipment required	On-orbit filling mechanisms; voltages applied across cells.
Particle sizes	≈ 50 to 70 microns, TCCE; and 10 to 50 microns for IIE & DDE.
Fluids used	Silicone oils, glycerol, water, aqueous solutions of copper sulphate with sulphuric acid.
Crew operations & functions	Test cell insertion and changeout.

Basis Experiment f12 – Critical Point Phenomena

Imaging views & directions	Direct visualization of fluid; fluid may appear opaque and turbid
Visual resolution	0.5 to 80 microns
Field of view	12 to 15 mm
Fluid & particle speed's	N/A
Framing rates	1 to 200 fps
Exposure duration per image	Variable, ranging from 5 to 1000 msec.
Image processing duration	About 5 min/hr for exp. duration; at high frame rates about 1 min. duration.
Imaging equipment required	B/W digital imaging camera.
Optical diagnostics	B/W imaging; interferometry (e.g., TGI); sm and lg angle light scattering.
Non-laser light sources	Dffuse white or LED collimated light.
Laser light sources	Laser required for light scattering and interferometry; TEMoo mode; > 20 cm coherence; 1: 1,000,000 freq stab.; 10 microrad/day pt. stability.
Laser light mgmt	16 mm beam dia. for interferometry.
Pres. measurement & cont'l	Ambient pressures around cells; internal press. ranging from 30 to 210 atm; meas. req'd with +/- 1:1,000,000 accuracy; no control necessary.
Temp. measurement & cont'l	ambient temp's around cell, 20 to 25 deg-C; maintained to within +/- 0.5 deg-C; cont'l cell internal temp's, < +/- 0.01 mK; temp. stability < 0.05 mK/hr; & temp. grad. < 0.001 mK/cm.
Voltage meas. & cont'l	500 to 1000 volts for elec. field study.
G-jitter freq's	for ALL frequencies, amplitudes should be less than 0.001 g/go
DC g-levels	< 0.00001 g/go for 30 min. durations
Instrumentation/accuracies	Measure cell fluid temp. to < +/- 0.005 mK accuracy; critical temp. of candidates fluids: water: 374.15; Xenon: 16.57; carbon dioxide: 30.95; and sulphur hexafloride: 45.55 deg-C.
Sampling rates/durations	2 to 5 temp. & volt/curr. channels; up to 10 Hz sufficient .
Temp. field resolution	N/A
Velocity field resolution	N/A
Concentration field resolution	N/A
Experiment duration	2 to 20 days for a complete run.
Number of tests	10 to 20.
Experiment matrix & ranges	3 to 4 fluids; 2 to 10 runs per fluid.
PI TC/equip dimensions	Fluid volumes up to 10 ml; fluid cells about 3 to 6 cm dia x 3 to 12 cm; overall thermostat dimensions about 15 cm dia x 25 cm; some cells to have variable volume capability.
Special equipment required	Photomultiplier to support light scattering; thermostat for temp. cont'l; stimuli such as mag. stirring, acoustic fields and electric fields.
Particle sizes	Many length scales & density fluctuations are effective particles.
Fluids used	Sulfur hexafloride, xenon, carbon dioxide.
Crew operations & functions	Cell insertion and changeout .

Basis Experiment f13a – Multiphase Flow Boiling

Imaging views & directions	View flow in a conduit, with & w/o boiling; study flow regimes; one view near mixer & one near end of straight section; ortho. views may be req'd.
Visual resolution	50 microns req'd (20 micron preferred) for 1 mm FOV; scale up for lg. FOV's.
Field of view	Sm. FOV of about 1 mm; also larger FOV from 10 to 30 cm.
Fluid & particle speed's	Ranging from 0.05 to 10 m/sec.
Framing rates	Ranging from 30 to 1000 fps (up to 5000 fps desired); acquired periodically in 30 to 60 sec durations.
Exposure duration per image	No data yet.
Image processing duration	Experiment duration.
Imaging equipment required	B/W digital imaging cameras; IR camera possible for heating surfaces.
Optical diagnostics	B/W video imaging; PIV flow studies.
Non-laser light sources	Diffuse white background lighting.
Laser light sources	TBD laser for PIV.
Laser light mgmt	TBD laser sheet for PIV.
Pres. measurement & cont'l	No external pressure constraints; internal line pressures ranging from 1 to 10 atm; controlled to +/- 5%.
Temp. measurement & cont'l	No external temperature constraints; internal temps from –15 to 200 deg-C; controlled to +/- 0.5 deg-C.
G-jitter freq's	Sensitive to frequencies < 10 Hz.
DC g-levels	Less than 0.0001 g/go.
Instrumentation/accuracies	Various abs. press., press. diff., temp, void fraction, local velocity, wall shear, and film thickness measurements.
Sampling rates/durations	From 100 to 2500 Hz (up to 5000 Hz desired) from 30 sec to 10 min.; press. & temp. at lower rates/longer durations; void fraction, local velocity, wall shear, & thickness measurements at higher rates/shorter durations.
Temp. field resolution	N/A
Velocity field resolution	Gathered from imaging data; expected velocities from 0.05 to 10 m/sec.
Concentration field resolution	N/A
Experiment duration	2 to 10 minutes.
Number of tests	400 to 500.
Experiment matrix & ranges	Various liq. and gas flow rates (5x5); line diameters (3x), pressures, temp, and fluid-gas combos (2x3).
PI TC/equip dimensions	Straight run tubing lengths with L/D ratios > 100; plan for 5, 7.5, and 10 mm dia tubes; parallel test sections may be required; other possible geometry of interest is heliocoil.
Special equipment required	Pumps, separators, mixers, and accumulators included in this flow loop; may be line heaters (for vapor).
Particle sizes	Some particles may be req'd for PIV studies.
Fluids used	Liq. mix.: water+glycerin, water+surfactants, fluorinerts, and ammonia; gasses: air, N2, Ar, & Xe.
Crew operations & functions	Depending upon design: test section and/or fluid changeout.

Basis Experiment f13b – Multiphase Flow Boiling

Imaging views & directions	Image bubble nucleation, growth, and departures from a flat heater surface with known nucleation locations; two orthogonal views of bubble(s).
Visual resolution	150 microns for PF5060; and 250 microns for water; DOF: 10 cm (PF5060) and 17 cm (water).
Field of view	12x12 cm (PF5060); 25x25 cm (water).
Fluid & particle speed's	N/A
Framing rates	10 fps for PF5060 and 5 fps for water.
Exposure duration per image	No data yet.
Image processing duration	15 to 20 minutes per test.
Imaging equipment required	B/W digital camera.
Optical diagnostics	General imaging of bubble; interferometry for temps;
Non-laser light sources	Diffuse white background lighting.
Laser light sources	λ=532 nm should be ok; 100 mW power, at least 1 m coherence length.
Laser light mgmt	Beam diameter of about 1 mm is sufficient..
Pres. measurement & cont'l	Chamber pressures to range from 110 to 150 kPa; controlled to +/- 1 kPa; measured to +/- 0.5 kPa.
Temp. measurement & cont'l	No control on outside temps; chamber temps from 59 to 102 deg-C.
G-jitter freq's	Sensitive to frequencies below 10 Hz.
DC g-levels	About 0.0002 g/go or less.
Instrumentation/accuracies	32 temperature sensors to mainly characterize heater; measure to an accuracy of +/- 0.1 deg-C.
Sampling rates/durations	32 channels for ea. cell; 1 Hz for water and 2 Hz for PF5060; for exp. duration.
Temp. field resolution	Measure temp field to within 1 cm around bubble; TBD accuracy.
Velocity field resolution	N/A
Concentration field resolution	N/A
Experiment duration	15 to 20 minutes after equilibration.
Number of tests	50 to 60 tests.
Experiment matrix & ranges	Systems pressures (3 values); super heat (4 values); choice of fluids (2); and heater types (2).
PI TC/equip dimensions	Two boiling chambers: 20x20x30 cm with 15 cm dia heating surface (PF5060); and 35x35x75 cm with 30 cm dia heating surface (water.)
Special equipment required	Test chamber with pressure control; heat power draw of 400 to 1000 W.
Particle sizes	N/A
Fluids used	Two fluids: PF5060 and water.
Crew operations & functions	Chamber insertion and changeout.

Basis Experiment F14 – Mechanics of Granular Media

Imaging views & directions	Study motion of spheres through various windows (about 4) in the side of the racetrack cell.
Visual resolution	20 to 60 microns.
Field of view	20 x 20 to 40 x 40 cm .
Fluid & particle speed's	Less than 60 cm/sec.
Framing rates	General 30 fps; occasionally up to 500 fps with the smaller FOV's.
Exposure duration per image	Less than 150 micro-sec
Image processing duration	Such that at least 10,000 frames acquired (on the order of 100 sec) at each viewing window.
Imaging equipment required	B/W digital video camera.
Optical diagnostics	General B/W video imaging.
Non-laser light sources	Diffusive white background lighting.
Laser light sources	N/A
Laser light mgmt	N/A
Pres. measurement & cont'l	Cell pressures between 700 to 1200 mbar; measured to +/- 5% accuracy; no control.
Temp. measurement & cont'l	15 to 25 deg-C measured to an accuracy of +/- 1 deg-C; no control.
Humidity meas. & cont'l	Between 50 and 90% measured to an accuracy of +/- 5%; no control.
G-jitter freq's	No data yet.
DC g-levels	Less than 0.002 g/go.
Instrumentation/accuracies	Press., & humidity measured to +/- 5%; temp. to +/- 1%; no control necessary; measure belt velocity to +/- 1%, cont'l to +/- 2%.
Sampling rates/durations	Pressure, temperature, and humidity data at 1 Hz.
Temp. field resolution	N/A
Velocity field resolution	Record images of moving particle-spheres
Concentration field resolution	Record images to distinguish small spheres from large spheres dist.
Experiment duration	10 to 20 minutes
Number of tests	10 to 20
Experiment matrix & ranges	Parameters include: particles sizes, masses ratio (materials), diameter ratio, and volume fractions, and inner belt velocities.
PI TC/equip dimensions	Inner cell dimensions: 2x1.5x25 cm (sm sphere); 4.5x3x 60 cm (lg sphere).
Special equipment required	High frame rate camera.
Particle sizes	Sm. sphere dia. range from 1.5 to 3.5 mm; lg sphere dia. 1.25 x sm. sphere
Fluids used	Spheres are in air.
Crew operations & functions	Test cell insertion and changeout.

Basis Experiment f15 – Shear Rheology of Complex Fluids

Imaging views & directions	Two cases: foam (low liquid content) and suspensions (high liquid content) (A/B); image bubbles along walls (to measure slip); using general and micro imaging; image plane, ~ 1 bub. dia. from wall
Visual resolution	Resolution should be met with a pixel density of 500 x 500 (< 1% bub. dia.)
Field of view	Var. up to 10 bub. dia.; DOF of 0.2 of smallest bubble size.
Fluid & particle speed's	For A: ~ 50 cm/sec (for 100 rpm & 10 cm dia cell); for B: up to 160 cm/sec.
Framing rates	For A: 30 fps; for B: 30 to 1000 fps.
Exposure duration per image	No data yet.
Image processing duration	Exp. duration, for A; 2 min/run for B.
Imaging equipment required	B/W CCD video (A,B), video microscope (A only).
Optical diagnostics	General imaging (A,B); following for A: microscopic imaging; diffusive transmitted spectroscopy (DTS); diffusive wave spectroscopy (DWS).
Non-laser light sources	Diffuse white background lighting.
Laser light sources	For A: solid state, cw, single freq.; coherence length > 10 m; λ=532 nm ok; 50 to 100 mW probably req'd
Laser light mgmt	Beam diameter 1 mm (A only).
Pres. measurement & cont'l	Near 1 atm; and cont'd in the cell to +/- 0.01/0.03 atm (A/B) for ALL samples.
Temp. measurement & cont'l	Ranging 20 to 30 deg-C; but cont'l to +/- 0.2/2 deg-C (A/B) for ALL samples
G-jitter freq's	No data yet.
DC g-levels	Less than 0.01 / 0.00003 g/go (A/B).
Instrumentation/accuracies	For A and B: measure shear strain, step-strain, shear strain rate, and force (wall shear stress) in rheometer; bubble velocities and diameters and vol. frac. for B only.
Sampling rates/durations	16 channels at 10 kHz/2 min (B only).
Temp. field resolution	N/A
Velocity field resolution	N/A
Concentration field resolution	Vol. frac., .1 to .2, fctn of couette gap (B)
Experiment duration	1000 to 1200 min (A), 15 to 30 min (B).
Number of tests	About 30 to 50 tests (A & B).
Experiment matrix & ranges	For A: 5 to 40% liq. (12x); shear rate .001 to 100 rpm (6x); fluid combo (3x); for B: bub. dia. (2x), vol. frac. (0.1, 0.15, 0.2), and shear rates (5 to 40+ 1/sec).
PI TC/equip dimensions	For A: rheometer ~ 5 to 10 cm dia & 1 to 2 cm high (non-wet. surf.); 0.001 to about 100 rpm; ~100 ml liq. vol; for B: two conc. cyl., outer (rotating) cyl, 30 cm, inner cyl. 24-cm. dia.
Special equipment required	Providing containment in a rheometer device where only one surface rotates.
Particle sizes	Bub. dia. 10 to 500 microns (A); and 2 to 3 mm (B)
Fluids used	For A: aqueous solution of 0.8% sodium-AOS plus with either 0.2% dodeconol, or 1% butanol, or 0.2% polyacrylic acid; for B: aqueous 0.05 M salt solution of $MgSO_4$ /no surfactants.
Crew operations & functions	Loading cells; clean or changeout cell; check for inhomogeneities in bubbles, suspension/loading removal.

Basis Experiment f16 – Mesoscopic Studies of Colloids and Complex Fluids

Imaging views & directions	Viewing cell crystal structures and various light scattering images and active manipulations through multiple microscope ports.
Visual resolution	About 0.25 micron to resolve small crystal structures.
Field of view	Variable FOV from 0.1 to 1 mm; also overall FOV 3 x 3 cm.
Fluid & particle speed's	N/A
Framing rates	30 fps / 1 frame per hour.
Exposure duration per image	No data yet.
Image processing duration	Exp. duration every 15 to 30 min.
Imaging equipment required	B/W digital imaging camera, color digital camera, microscope, intensified camera for fluorescience imaging.
Optical diagnostics	Confocal microscopy, video microscopy (DIC, phase contrast, bright & dark field imaging), fluorescence microscopy, laser tweezers & micro-rheology, light Bragg, scattering (dynamic & static); and spectrophotometry.
Non-laser light sources	Kohler illumination; diffuse white light.
Laser light sources	Laser req'd for various LLS diagnostics; λ = 532 nm, 1 to 30 mW power; var. beam dia. up to 0.6 mm; stability +/- 0.1%; coherence of at least 1 m; also need λ = 1064 nm at about 1 W for laser tweezers.
Laser light mgmt	capability to have laser beam incident and receiving optics at various angles.
Pres. measurement & cont'l	about 1 atm; no control necessary .
Temp. measurement & cont'l	20 – 25 deg-C controlled to +/- 1.0 deg-C; also capability to impose temp. grad on samples (ΔT=20 deg-C).
G-jitter freq's	No data yet.
DC g-levels	Less than 0.0001 g/go.
Instrumentation/accuracies	Temp. with +/- 0.1 deg-C accuracy.
Sampling rates/durations	Temp. data rate at 1 Hz.
Temp. field resolution	N/A
Velocity field resolution	N/A
Concentration field resolution	N/A
Experiment duration	1 hour to 5 days (avg 24 hours).
Number of tests	Continual periodic monitoring of all tests ($\approx$ 150 to 1000 micro. samples).
Experiment matrix & ranges	Parameters: volume fraction, types of fluids & particles; temp. grads; particle dia., template types, and dia. ratios.
PI TC/equip dimensions	Microscopic samples from about 1 x 1 x 0.1 mm to 1 x 1 x 0.1 cm.
Special equipment required	Test cells able to accommodate homogenizations (e.g., mag. stirrers); correllator boards, and DLS detectors.
Particle sizes	Typically PMMA-PHSA particles from 10 nm to 5 microns; also polystyrene, silica, zinc sulphide.
Fluids used	Decalin & tetralin mixtures,optical immersion oil, water.
Crew operations & functions	Test cell insertion and changeouts. Immersion oil clean-up and injection.

Appendix F - Data Tables for Combustion Experiments

F. DATA TABLES FOR COMBUSTION EXPERIMENTS

EXPERIMENTAL OPERATING CONDITIONS

BASIS EXPERIMENT NUMBER	TITLE	FUEL(S)	OXIDANT(S)	DILUENT(S)	INITIAL PRESSURE	TIME PER TEST	"MINIMUM" NUMBER OF TESTS	IGNITER	DUCT/CHAMBER DIMENSIONS	FLOW	INITIAL TEMPERATURE	"QUASI-STEADY" ACCELERATION ENVIRONMENT
c1	Gas Jet Diffusion Flames	methane, propane	O2 (15-30%)	N2	.5 - 2 atm	350-600 sec	20	Hot wire, 1475 K	L/D = 1.5-2.5 vol = 0.05-0.1 m3	0-30 scc/sec fuel flow	290-300 K	10e-4 or less
c2	Structure of Flame Balls at Low Lewis Numbers	hydrogen, methane	O2 + diluent	N2, CO2, Ar, He, SF6	1 - 3 atm	400-500 sec	20	Spark, .001-1 joule	L/D = 1.0-1.5 vol = 0.02-0.05 m3	nil	290-300 K	4x10e-4 or less
c3	Ignition and Flame Spread Over Liquid Fuel Pools	1-butanol, 1-propanol, n-decane, methanol	O2 + diluent	He, Ar, CO2	~1 atm	600-1200 sec	10	Hot wire, 1275 K	L = 40-45 cm D = 10-12 cm H = 10-12 cm	0-4000scc/sec oxidizer flow	268-315 K	10e-4 or less
c4	Diffusive and Radiative Transport in Fires	Solid PMMA	O2 (35-70%)	N2	~1 atm	600-1200 sec	6	Hot wire	L = 15-20 cm D = 10-12 cm H = 10-12 cm	0-2000 scc/sec oxidizer flow	291-301 K	10e-4 or less
c5	Smoldering Combustion	Polyurethane foam	O2 (25-35%)	N2	~1 atm	1000-8000 sec	10	Flat plate igniter (ceramic)	L/D = ~1 vol = 0.02-0.05 m3	0-100 scc/sec oxidizer flow	288-300 K	10e-3 or less
c6	Droplet Combustion	n-heptane, n-decane, methanol	O2 (10 - 50 %)	N2, He	0.2 - 1 atm	700-850 sec	60	Hot wire, spark	L/D = 0.95-1.5 vol = 0.05-0.08 m3	nil	290-300 K	10e-5 or less
c7	Laminar Soot Processes	ethylene, propylene, acetylene, propane	O2 (21%)	N2	0.45 - 1 atm	350-600 sec	8	Hot wire, 1050K	L/D = 1.5-2.5 vol = 0.05-0.1 m3	0-5 scc/sec fuel flow	280-320 K	10e-4 or less
c8	Soot Measurements in Droplet Combustion	n-heptane, n-decane, methanol, toluene	O2 (to 50%)	N2, He, Ar, CO2	0.2 - 1 atm	700-850 sec	60	Hot wire, spark	L/D = 0.95-1.5 vol = 0.05-0.08 m3	nil	290-300 K	10e-5 or less
c9	Unsteady Burning of Contained Reagents	H2 (24 - 35 mol%) in Ar	O2 (17 - 31%)	He, Ar	0.5 - 1 atm	350-500 sec	15	Spark (2100-2300 K at ignition)	L = 25-30 cm D = 25-30 cm H = 8.5-10 cm	nil	290-300 K	10e-5 or less
c10	Solid Fuels Flammability Boundary	Misc. paper, cloth, polymers	O2 (10 - 21%)	N2	~1 atm	600-1200 sec	15	Hot wire	L = 28-35 cm D = 11-15 cm H = 11-15 cm	0-1500 scc/sec oxidizer flow	290-300 K	10e-5 or less
c11	Radiative Ignition and Transition to Flame Spread	Filter paper, polyethylene, PMMA	O2 (21 - 50%)	N2	~1 atm	600-1500 sec	20	Hot wire, laser	L = 24-30 cm D = 12-15 cm H = 16-18 cm	0-4000 scc/sec oxidizer flow	290-300 K	10e-4 or less

SELECTED MEASUREMENT REQUIREMENTS

BASIS EXPERIMENT NUMBER	TITLE	VISIBLE IMAGING FLELD OF VIEW (cm x cm)	VISIBLE IMAGING RESOLUTION (mm)	VISIBLE IMAGING FORMAT	INFRARED IMAGING FLELD OF VIEW (cm x cm)	INFRARED IMAGING RESOLUTION (mm)	INFRARED IMAGING FORMAT	ULTRAVIOLET IMAGING FLELD OF VIEW (cm x cm)	ULTRAVIOLET IMAGING RESOLUTION (mm)	ULTRAVIOLET IMAGING FORMAT	PRESSURE MEASUREMENTS RANGE (atm)	PRESSURE MEASUREMENTS ACCURACY (atm)
c1	Gas Jet Diffusion Flames	(20 - 30)x(12 - 18) 1 - 2 views	0.5 - 2	color	(20-30)x(20-25) sideview	0.5 - 2	b&w	n/a	n/a	n/a	0.5 - 2.0	0.001 - 0.2
c2	Structure of Flame Balls at Low Lewis Numbers	(25-35)x(25-35) 2 orthogonal views	0.5 - 1	color. b&w intensified	(25-35)x(25-35) 1 view	0.5 - 2	b&w	(2.9-3.1)x(2.1-2.3) 1 view	1.5 - 2.5	b&w intensified	0.2 - 6.1	0.002 - 0.2
c3	Ignition and Flame Spread Over Liquid Fuel Pools	(28-35)x(2-8) 2 orthogonal views	1 - 2	color	(9 - 11)x(2 - 8) top view	0.15 - 0.3	b&w	n/a	n/a	n/a	1.0 - 1.5	0.005 - 0.01
c4	Diffusive and Radiative Transport in Fires	(1.9-2.1)x(0.9-1.1) 1 sideview	0.05 - 0.08	b&w intensified	(2 - 3.1)x(1 - 2.1) sideview	0.2 - 0.3	b&w	(1.9-2.1)x(0.9-1.1) sideview	0.05 - 0.08	b&w intensified	0.8 - 1.2	0.0005 - 0.001
c5	Smoldering Combustion	(18-22)x(14-16) 1 sideview	2 to 5	color	n/a	n/a	n/a	n/a	n/a	n/a	0 - 3	0.05 - 0.1
c6	Droplet Combustion	(3.3-3.5)x(3.3-3.5) droplet view, flame view	0.018 - 0.036	color, b&w intensified	n/a	n/a	n/a	(3.5-4.5)x(3.5-4.5) 1 view	0.09 - 0.18	b&w intensified	0.2 - 1.1	0.01 - 0.02
c7	Laminar Soot Processes	(8-10)x(6-8) 2 orthogonal views	0.75 - 1	color	n/a	n/a	n/a	n/a	n/a	n/a	0.5 - 2.0	0.05 - 0.1
c8	Soot Measurements in Droplet Combustion	(3.3-3.5)x(3.3-3.5) droplet view, flame view	0.018 - 0.036	color, b&w intensified	n/a	n/a	n/a	(3.5-4.5)x(3.5-4.5) 1 view	0.09 - 0.18	b&w intensified	0.2 - 1.1	0.01 - 0.02
c9	Unsteady Burning of Contained Reagents	(25-35)x(2-4) 2 orthogonal views	0.2 - 0.5	color, b&w intensified	(25 - 35)x(9 - 10) sideview	0.08 - 0.12	b&w	n/a	n/a	n/a	0.5 - 10	0.005 - 0.1
c10	Solid Fuels Flammability Boundary	(10-20)x(10-12) 2 orthogonal views	0.2 - 0.5	color	(10-20)x(10-12) 1 - 2 views (side & top)	0.2 - 0.5	b&w	(10-20)x(10-12) sideview	0.2 - 0.5	b&w intensified	0.8 - 1.2	0.0005 - 0.001
c11	Radiative Ignition and Transition to Flame Spread	(14-16)x(10-12) 2 side views, 1 top view	0.2 - 0.5	color	n/a	n/a	n/a	n/a	n/a	n/a	0.8 - 1.2	0.0005 - 0.001

Appendix F - Data Tables for Combustion Experiments

SELECTED MEASUREMENT REQUIREMENTS (continued)

BASIS EXPERIMENT NUMBER	TITLE	GAS PHASE TEMPERATURE (POINT MEASUREMENTS)		CONDENSED PHASE TEMP. (POINT MEASUREMENTS)		SOOT MEASUREMENTS		POINT VELOCITY MEASUREMENTS		VELOCITY IMAGING	RADIOMETRY
		TEMP. RANGE (K)	ACCURACY (K)	TEMP. RANGE (K)	ACCURACY (K)	FLELD OF VIEW (cm x cm)	RESOLUTION (cm x cm)	VELOCITY RANGE (cm/sec)	ACCURACY (cm/sec)	FIELD OF VIEW (cm x cm)	
c1	Gas Jet Diffusion Flames	270 - 1800	10 to 20	n/a	n/a	n/a	n/a	5 to 5000	1 to 50	n/a	yes
c2	Structure of Flame Balls at Low Lewis Numbers	300 - 2000	10 to 50	n/a	n/a	n/a	n/a	0 to 20	0 to 1	n/a	yes
c3	Ignition and Flame Spread Over Liquid Fuel Pools	260 - 1800	3 to 30	265 - 350	0.2 - 0.3	n/a	n/a	1 to 40	0.25 to 2	(2.5 - 7)x(2 - 8)	no
c4	Diffusive and Radiative Transport in Fires	300 - 1800	10 to 20	290 - 800	2.7 - 8.0	n/a	n/a	1 to 30	0.25 to 3	n/a	yes
c5	Smoldering Combustion	290 - 350	2 to 5	290 - 1100	5 to 10	n/a	n/a	n/a	n/a	n/a	no
c6	Droplet Combustion	300 - 500	1 to 5	n/a	n/a	n/a	n/a	n/a	n/a	n/a	no
c7	Laminar Soot Processes	280 - 1000	3 to 70	n/a	n/a	(8-9)x(3-4)	(0.2-0.3)x(0.05-0.1)	n/a	n/a	n/a	yes
c8	Soot Measurements in Droplet Combustion	300 - 500	1 to 5	n/a	n/a	(2.5-3.5)x(2.5-3.5)	(0.01-0.02)x(0.01-0.02)	n/a	n/a	n/a	no
c9	Unsteady Burning of Contained Reagents	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	no
c10	Solid Fuels Flammability Boundary	300 - 1500	10 to 50	n/a	n/a	n/a	n/a	n/a	n/a	n/a	yes
c11	Radiative Ignition and Transition to Flame Spread	n/a	n/a	n/a	n/a	(0.03-0.04)x(2.9-3.1)	(0.04-0.05)x(0.04-0.05)	n/a	n/a	(14-16)x(10-12)	no

SELECTED MEASUREMENT REQUIREMENTS (continued)

BASIS EXPERIMENT NUMBER	TITLE	GAS PHASE TEMPERATURE FIELD MEASUREMENTS				CONDENSED PHASE TEMPERATURE FIELD MEASUREMENTS				ACCELERATION MEASUREMENT	
		FLELD OF VIEW (cm x cm)	SPATIAL RESOLUTION (mm)	TEMPERATURE RANGE (K)	TEMPERATURE RESOLUTION (K)	FLELD OF VIEW (cm x cm)	SPATIAL RESOLUTION (mm)	TEMPERATURE RANGE (K)	TEMPERATURE RESOLUTION (K)	RANGE (g/g0)	ACCURACY (%)
c1	Gas Jet Diffusion Flames	(15 - 20)x(15 - 20)	1 - 2	300 - 1800	50 - 60	n/a	n/a	n/a	n/a	10e-2 - 10e-6	5 to 15
c2	Structure of Flame Balls at Low Lewis Numbers	(15 - 20)x(15 - 20)	1 - 2	300 - 2000	50 - 60	n/a	n/a	n/a	n/a	10e-2 - 10e-5	5 to 15
c3	Ignition and Flame Spread Over Liquid Fuel Pools	(8 - 12)x(8 - 12)	0.15 - 0.3	300 - 2000	50 - 60	(9-11)X(2.8-3.2)	0.25 - 0.3	260 - 350	0.2 - 0.3	10e-2 - 10e-5	5 to 15
c4	Diffusive and Radiative Transport in Fires	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	10e-2 - 10e-6	5 to 15
c5	Smoldering Combustion	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	10e-2 - 10e-5	2 to 4
c6	Droplet Combustion	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	10e-2 - 10e-6	2 to 4
c7	Laminar Soot Processes	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	10e-2 - 10e-4	5 to 15
c8	Soot Measurements in Droplet Combustion	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	10e-2 - 10e-6	2 to 4
c9	Unsteady Burning of Contained Reagents	(25 - 35)x(9 - 10)	0.08 - 0.12	1600 - 2900	50 to 100	n/a	n/a	n/a	n/a	10e-2 - 10e-6	5 to 15
c10	Solid Fuels Flammability Boundary	(10-12)x(10-12)	0.2 - 0.3	300 - 1500	10 to 30	(10-20)x(10-12)	0.2 - 0.5	300 - 800	5 to 10	10e-2 - 10e-6	5 to 10
c11	Radiative Ignition and Transition to Flame Spread	(0.05-0.06) x (2.9-3.1)	0.4 - 0.5	300 - 1800	40 to 50	(5-10)x(4-8)	0.25 - 0.5	300 - 1300	40 to 60	10e-2 - 10e-6	5 to 15

Appendix G - Reagents for Fluids and Combustion Experiments

G. REAGENTS FOR FLUIDS AND COMBUSTION EXPERIMENTS

G.1 REAGENTS FOR FLUIDS EXPERIMENTS

The basis experiments identify a large number of fluid reagents which are typically employed in Earth-based measurements. These are summarized below.

It is expected that not all “typical” reagents will be acceptable in a manned space-based laboratory due to the need to minimize risks; however, it is desired that the facility consider the implications carefully with a goal of accommodating as many unique fluids as possible.

Facing table displays the reagents identified in the basis experiments for fluids and highlights selected physical properties of potential significance.

FLUIDS PROPOSED FOR BASIS EXPERIMENTS (See APPENDIX A) AND SELECTED PROPERTIES

Fluid	Experiment Number	Surface Tension, s (dynes/cm)	Density, r (gm/cm3)	s/r (cm3/sec2)	Refractive Index	Special Considerations
Organic Fluids						
Acetone	f1		0.7899		1.3588	flammable
Butyl benzoate	f9	30	0.89	33.7		flammable
Carbon dioxide	f12			1.101		asphyxiant
Castor oil	f6, f9	8	0.96	8.3		flammable
Cyclohexane	f5		0.8102		1.4465	flammable
Decalin	f4					flammable
Dialkylphthalate esters	f11					flammable
Diethyleneglycol	f9		1.1197		1.4472	flammable
Ethanol	f9, f10	22	0.79	27.8	1.3592	flammable
Fluorinerts	f1, f8, f13a, f13b	15	1.96	7.6		non-flammable, dielectric
Glycerin	f11, f13a	63	1.2613	50	1.4729	flammable
Heptane	f10		0.6837		1.3878	flammable
Hexane	f7	18	0.6603	22.5	1.3751	flammable
Methanol	f1	23	0.7914	29.1	1.3288	flammable
Mineral oil	f6					flammable
Pentane	f1		0.6262		1.3575	flammable
Polystyrene	f3					flammable
Tetrahydrofuran	f5					flammable
Tetralin	f4		0.9702		1.5413	flammable
Toluene	f5, f10					flammable
Inorganic Fluids						
Ammonia	f13a		1.325		1.0004	asphyxiant, irritant
Fused quartz powder	f14				1.4564	
Liquid metals	f11					corrosive
Magneto rheolgical 'fluids'						
Silica 'aerogel'	f5					
Silicone oils	f2, f6, f8, f9	21	0.95	21		
Sulfur hexafluoride	f12					asphyxiant
Water (and salt solutions)	f5, f6, f13a,b, f11, f12	70	1	70	1.333	corrosive
Xenon	f12					non-flammable, asphyxiant

G.2 REAGENTS FOR COMBUSTION EXPERIMENTS

The basis experiments identify a large number of fuels reagents which are typically employed in Earth-based measurements; these are summarized below. It is expected that not all 'typical' fuels will be acceptable in a manned space-based laboratory due to the need to minimize risks, however, it is desired that the facility consider the implications carefully with a goal of accommodating as many unique fuels as possible.

It is recognized that clean-up of exhaust products is necessary and that some fuels and diluents may be limited or excluded by the constraints imposed by the exhaust processing system.

In addition to the fuels identified, the required oxidizer for all experiments is oxygen gas.

For several experiments, the relative concentration of fuel and oxidizer is adjusted with a diluent. The following diluents are identified in the basis experiments:

DILUENT	EXPERIMENT NUMBER
nitrogen, N_2	(c1, c2, c4, c5, c6, c7, c8, c10, c11)
carbon dioxide, CO_2	(c2, c3, c8)
argon, Ar	(c2, c3, c8, c9)
helium, He	(c2, c3, c6, c8, c9)
sulfur hexafluoride, SF_6	(c2)

Facing table displays the fuels identified in the basis experiments for combustion.

FUELS PROPOSED FOR COMBUSTION BASIS EXPERIMENTS (SEE APPENDIX B)

FUEL	EXPERIMENT NUMBER
Hydrocarbons	
methane	c1, c2
propane	c1, c7
n-decane	c3, c6, c8
Unsaturated hydrocarbons	
ethylene	c7
propylene	c7
acetylene	c7
toluene	c8
Alcohols	
1-butanol	c3
1-propanol	c3
methanol	c3, c6, c8
Organic solids	
Polymethylmethacrylate (PMMA)	c4, c11
Polyurethane (foam)	c5
Cellulose (filter paper)	c11
Polyethylene	c11
Other combustible gas	
Hydrogen	c2, c9

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